

TRANSACTIONS AMERICAN GEOPHYSICAL UNION

Volume 31

FEBRUARY 1950

Number 1

SUMMARY OF THE GEOPHYSICAL INVESTIGATIONS ON THE GREAT EARTHQUAKE IN SOUTHWESTERN JAPAN ON DECEMBER 21, 1946

Takesi Nagata

Abstract--Chief results of various geophysical studies of the great earthquake in the Southwestern part of Japan on December 21, 1946, such as the distribution and magnitude of after shocks, some characteristics of the land deformation and tsunami accompanying the earthquake and prior to the earthquake, are summarized. The general aspect of markedly regular distribution of the land deformation relating to this earthquake is especially dealt with. The mode of vertical deformation of the whole area of Shikoku Island accompanying the earthquake was almost the reverse of that during the 30 years before the earthquake, while its progress with time before and after the earthquake shows a close relation between the occurrence of large earthquakes and the formation of marine terraces in this district.

General description of the earthquake--A great earthquake occurred in the Nankaido District in southwest Japan at 19^h19^m GMT December 20, 1946 (December 21, Japanese time). Its epicenter was determined to be at 33°0' N, 135°6' E. The distribution of seismic intensity of this earthquake is given in Figure 1. It will be seen that the area over which the earthquake was felt covered almost the whole central and western parts of Japan. This was one of the largest earthquakes that has been felt in Japan. Records show that 1443 people were killed and the number of houses destroyed directly by the earthquake was 2598, while 1451 were washed away by the accompanying tsunami.

Historically speaking, earthquakes as large as the present one have taken place intermittently in the Nankaido District, such as, for example, those of February 2, 1605, October 28, 1707, and December 24, 1854. According to historical records, the area where the earthquakes were felt was almost the same as for the present one. They were always accompanied by large tsunamis. It seems that the earthquake in 1946 was one of a closely related series.

Results of seismometric observations--Since the earthquake was so strong, perfect seismograms were not obtained in the epicentral region. The seismometric data from the chief stations in Japan are summarized in Table 1 [CENTRAL METEOROLOGICAL OBSERVATORY, 1947].

According to [KAWASUMI, 1947], the magnitude of this earthquake determined from the distribution of the seismic intensity was 6.5, this result corresponding to the total seismic energy of 10^{26} ergs. If we assume that the energy was accumulated as elastic energy in the Earth's crust with 10^{-4} as its breaking strain and $\lambda = \mu = (1/4) \times 10^{12}$ CGS, the volume necessary for the accumulation of the elastic energy would be a sphere 150 km in diameter in the case of uniform stress, or of 240 km in diameter in the case of pure shear only. At any rate, the hypocentral region of this earthquake is estimated to be larger than 100 km in linear dimension. This conclusion seems to harmonize well with the various facts relating to this earthquake.

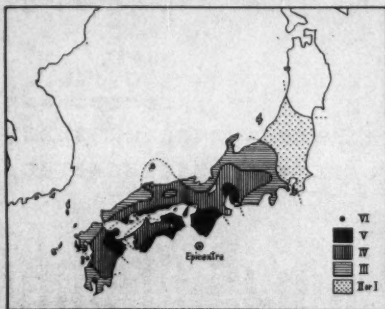


Fig. 1--Distribution of seismic intensity of the earthquake of December 21, 1946

After shocks--Many of the after shocks of this great earthquake were observed at the regular seismograph stations surrounding the earthquake area. However, since the distribution of these stations was not such as to make possible the recording of all the after shocks which were distributed over a wide area, several temporary stations were set in the neighborhood of the center of the earthquake area and operated for more than a month by the members of the Earthquake Research Institute and the Geophysical Institute of Tokyo University.

Table 1.--Summary of seismetric observations, earthquake of December 21, 1946

Observatory	Local civil time		Maximum amplitude				Seismic intensity	Initial motion				Duration of preliminary tremor		Epicentral distance
			N		E			N	E	Z				
			μ	μ	μ	μ								
Shimonisaki	h	m	s	μ	μ	μ	5	μ	μ	μ	m	s	km	
Owase	04	19	04.7	...	...	...	5	-17200	+900	(-)	0	04.5	50	
Kashiwabara	04	19	25.3	22500	17500	...	5	+470	-190.6	+448.7	0	15.4	128	
Tokushima	04	19	30.9	>2700	>2000	...	5	+1026	-43	...	0	13.5	162	
Kobe	04	19	32.5	27000	>26000	...	5	+850	-1300	+950	0	15.1	148	
Kanayama	04	19	34.2	93000	119000	32000	4	+389	-205	+480	0	12.0	190	
Osaka	04	19	36.3	...	...	15473	4	+389	+102	+310	0	28.3	210	
Sumoto	04	19	37.0	36000	36000	19333	4	+2150	+80	+740	0	18.8	168	
Kōchi	04	19	38.0	47000	...	...	5	+325	-282	+606	0	25.9	160	
Kyōto	04	19	38.4	19601	21251	...	5	+56	-375	+178	0	18.2	192	
Hikone	04	19	41.5	...	...	...	4	+36	-5	...	0	29.4	212	
Toyooka	04	19	48.3	24700	31250	600	5	+347	+42	+241	0	29.8	248	
Gifu	04	19	49.6	...	...	...	3	+270	-111	+239	0	29.9	276	
Tottori	04	19	50.0	2000	>2000	...	5	+116	+55	+38	0	15.1	272	
Ibukiyama	04	19	50.2	61800	...	...	4	+267	-63	...	0	30.0	290	
Nagoya	04	19	55.3	...	...	...	3	-8	-11	...	0	27.0	264	
Mishima	04	19	57.7	...	...	...	4	...	...	...	0	24.9	260	
Yonago	04	19	58.3	2620	1480	670	3	...	...	...	0	39.9	372	
Toyama	04	19	58.3	...	...	...	4	+44	-30	...	1	02.0	334	
Wajima	04	19	58.8	26000	20000	7000	3	...	...	...	0	24.7	416	
Shimonoseki	04	20	02.6	...	...	...	3	+28	+21	(+)	...	...	476	
Yokohama	04	20	08.5	34000	20000	2000	3	+10	-30	...	0	31.7	426	
Nagano	04	20	08.6	>25000	>3150	>2000	3	-13	-12	-18	0	54.8	438	
Miyazaki	04	20	09.7	16700	27500	9250	3	+11	+13	-0	0	59.4	450	
Kumamoto	04	20	11.1	>36000	>71250	>18220	4	...	...	+43	1	04.4	390	
Onsenake	04	20	12.4	...	...	...	4	-6.9	-56.5	+50.0	0	36.2	438	
Tokyo	04	20	12.5	...	...	...	4	...	-68.0	...	0	16.9	476	
Karuzawa	04	20	14.6	>2258	>3888	...	2	-10	-20	-22	0	60.0	466	
Maebashi	04	20	16.6	285	707	203	3	+7.5	+10.0	+2.0	0	52.5	444	
Kagoshima	04	20	19.0	>1650	>1500	...	3	+3.5	+3.6	...	1	01.7	472	
Fukuoka	04	20	20.2	30000	36000	15000	3	-11	-31	+11	0	59.1	478	
Onahama	04	20	20.8	>731	>644	>878	2	-4.0	-42.0	...	0	34.3	470	
Sendai	04	20	45.2	2292	5060	2075	2	-11	-13	-8	1	25.9	622	
Morioka	04	20	02.4	12000	9000	8000	1	-312	+273	-538	1	36.3	720	
							1	+5.2	+4.5	+3.0	1	32.2	856	

 Institute of
 Math. Science
 Grad. Math.
 Q11
 A52
 U331
 1950

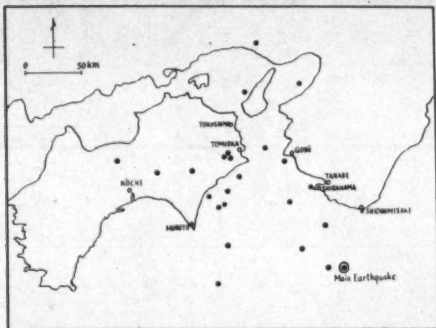


Fig. 2--Distribution of epicenters of after shocks

The distribution of the epicenters of comparatively intense after shocks observed during the month of January, 1947 is shown in Figure 2. It will be noted that the epicenters were spread over a wide area.

Crustal deformation relating to the earthquake--Great earthquakes are frequently accompanied by the deformation of the Earth's crust. The land deformation which accompanied this great earthquake was large and strikingly regular in its distribution.

Upheaval and subsidence of the sea coasts took place. The southern parts of both Shikoku and Kii Peninsula rose, while some northern parts subsided. Precise leveling surveys along all routes in Shikoku and Kii Peninsula were carried out during February 1947 to December 1948 by the GEOGRAPHICAL SURVEY BUREAU [1946]. The distribution of the leveling routes is shown in Figure 3, while the changes in elevation along those routes during the period 1929 to 1947 is given in Figure 4. It should be noted that almost the whole change in height accompanied the great earthquake. The contour lines of equal change shown in Figure 3 were derived from the results given in Figure 4.

The first precise leveling surveys in this region were carried out in 1895, and the second ones were done during 1929-1930. The changes in height during the period of 1895 to 1930 will be called here the pre-earthquake deformation.

The change in height of land accompanying the recent earthquake is, generally speaking, almost

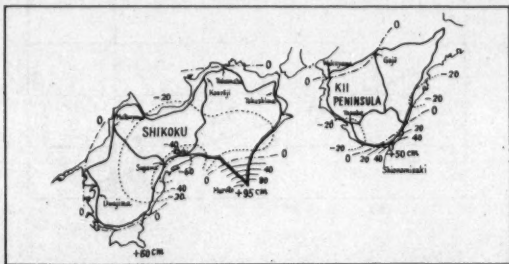


Fig. 3--Leveling routes and the vertical land deformation accompanying the earthquake in Shikoku and Kii Peninsula

K 1849

2/4/55-Direct-55

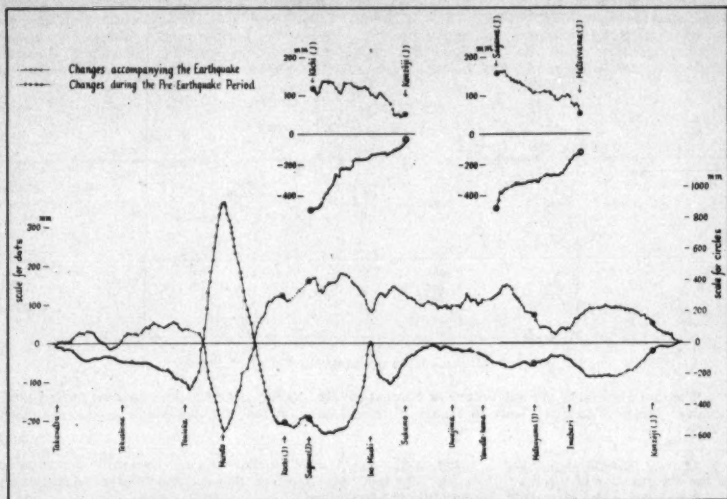


Fig. 4--Changes in elevation along leveling routes in Shikoku

reverse to that of the pre-earthquake, especially in Shikoku. Since the land deformation of Kii Peninsula during 1930-1947 should be the result not only of the present earthquake but also of the great earthquake in 1944, which occurred in the sea bottom east of Kii Peninsula, the circumstances here are somewhat different from those in Shikoku. Concerning the deformation of Shikoku, we may say that the law of reverse change holds even in minor undulations.

Comparing Figure 4 with a geological map, we can find that the areas that were subsiding in the pre-earthquake period correspond to the alluvial plains. The alluvial plains were probably subsiding in the pre-earthquake period, due to the compaction of the alluvial layer. The gradual subsidence of alluvial plains during the long years in the pre-earthquake period superposes on the above-mentioned general crustal deformation as a mere superficial phenomenon.

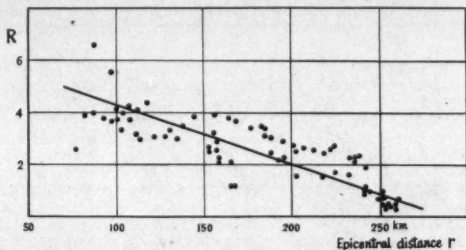


Fig. 5--Ratio of the vertical land deformations accompanying the earthquake and those of the pre-earthquake period R in relation to epicentral distance r

It has been recently found by OKUDA [1949] that the ratio R of the vertical deformation accompanying the earthquake ΔH to that during the pre-earthquake period $\Delta H'$ is a function of the epicentral distance, r . In Figure 5, the magnitudes of $R = -\Delta H/\Delta H'$ at various points (actually the mean values of five successive benchmark points), are plotted against the epicentral distance r . Here it will be seen that R becomes small (almost linearly) with the increase in the epicentral distance.

Summarizing these facts, we can express the general mode of the crustal deformation of Shikoku by the formula

$$\Delta H' = -R(r) (\Delta H + \Delta h)$$

where $R(r)$ denotes a linearly decreasing function of r , while Δh denotes the amount of subsidence of alluvium due to compaction. The true crustal deformation is $\Delta H + \Delta h$. This empirical formula may suggest the mechanism of the cause of the present great earthquake.

Since the vertical land deformation of Muroto Peninsula was large and regular, even in the pre-earthquake period, it will be a reasonable and convenient quantity for representing the general land deformation in the vicinity. Before the recent earthquake, the precise leveling surveys there were made in 1895, 1929, and 1935, while after the earthquake they were made five times (in January, February, March, and July in 1947 and in March in 1949) for the purpose of studying the progress of deformation.

According to the results of these surveys, the deformation during 1895 to 1935 shows that Muroto Peninsula had been inclining in the direction of $S10^\circ E$ with almost a constant velocity; the total tilt during the 40 years amounted to 1.4 . The change accompanying the present earthquake was exactly opposite in sense to that during 1895 to 1935, as already mentioned, while the changes during two years after the earthquake were not as monotonous as those before and accompanying the earthquake. Generally speaking, however, Muroto Peninsula is now inclining again to the southward, though it seems that a rather irregular westward tilt is superposed.

The general tendency of tilt of Muroto Peninsula before, accompanying, and after the earthquake, projected on a vertical plane directing $N10^\circ W - S10^\circ E$, is shown graphically in Figure 6.

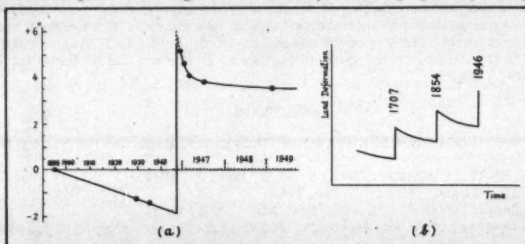


Fig. 6--(a) Tilt of Muroto Peninsula in the direction of $N10^\circ W - S10^\circ E$; (note that the time scale in the abscissa is enlarged from December 1946); (b) schematic mode of progress of land deformation of Shikoku

According to the old records, the mode of land deformation accompanying both the earthquake of 1707 and of 1854 in this district was almost the same as for the present one. Then, it will be seen that in this district a great earthquake accompanied by marked deformation of a definite type has occurred periodically with a period of 100 to 150 years. On the other hand, the inclination of the old beach lines on the marine terrace along the sea coast of Muroto Peninsula is proportional to the change in height of the present sea coast determined by the leveling survey [IMAMURA, 1944]. This fact may lead us to conclude that the Earth's crust in the vicinity of the origin of the present earthquake has continued the periodic deformation in such a manner as shown in Figure 6, where the abrupt changes correspond to the occurrence of earthquakes.

Tsunamis.—One remarkable phenomenon accompanying the present great earthquake was the arrival of a tsunami on the sea coasts of Shikoku and Kii Peninsula. The distribution of height of

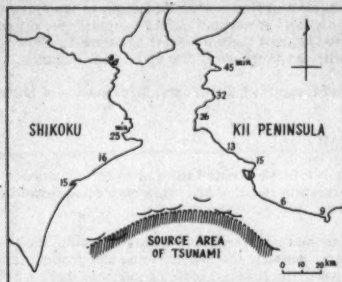


Fig. 7--The source area of tsunamis (numerals denote the difference between the arrival time in minutes of tsunami from that of the earthquake)

the tsunami in various bays were investigated in detail. It amounted, at the largest, to 6.0 m. The record of tsunami on the tide-gages on the western sea coast of the Kii Peninsula shows that the initial phase of tsunami was a decrease in sea level, and soon after a marked increase followed.

Next, the time interval T from the occurrence of the earthquake to the arrival of the tsunami at many points on the sea coast was investigated, the chief result being shown in Figure 7. Assuming that the velocity of tsunami is $\sqrt{gh}$, where h denotes the depth of the sea, we can obtain the possible locus of the origin. The result of estimate is shown also in Figure 7; the locus curves do not converge to a point. This fact may show that the origin of tsunami was not a small area but was fairly large, surrounding the epicenter of the earthquake. Comparing the above-mentioned conclusion with the fact that the land deformation took place in the wide area including Shikoku and Kii Peninsula, we can assume that the crustal movement of the sea bottom, which caused the tsunamis, also had a wide area.

Miscellaneous-work--In the earthquake area, various other geophysical phenomena were also observed by us. They were, for instance, the earth-current measurements, continuous observations of tilting motion of the Earth's surface, geophysical measurement of luminous phenomenon, and others. The results of those observations, however, will be omitted here.

In concluding, the writer desires to express his sincere thanks to R. Grant, Chief of the Mining and Geology Division, Natural Resources Section, GHQ, and to S. K. Neuschel, Chief of Pacific Geological Surveys Section, Military Geology Branch, U. S. Geological Survey, for their encouragement for this work and their kindness in communicating it to this journal. His hearty thanks are also due to N. Fukushima for his assistance throughout the whole study, to T. Asada and J. Suzuki for their assistance in the seismometric work, to A. Okada, Y. Harada and K. Hirao for their assistance in the leveling surveys.

References

- CENTRAL METEOROLOGICAL OBSERVATORY, Provisional Report of the Nankai-Do Great Earthquake, 1947.
 GEOGRAPHICAL SURVEY BUREAU, Review, no. 6, January, 1949.
 IMAMURA, G., Japan Islands, 50 pp., Tokyo, 1944.
 KAWASUMI, H., Suppl. Mem. Bull. Earthq. Res. Inst., no. 6, 1947.
 OKUDA, T., Read before the Annual Meeting of Physical Society of Japan, April, 1949.

Geophysical Institute,
 Faculty of Science,
 Tokyo University,
 Tokyo, Japan

(Communicated manuscript received December 31, 1948; and as revised September 2, 1949; open for formal discussion until July 1, 1950.)

THE HEIGHT OF EMISSION LAYERS IN THE UPPER ATMOSPHERE

F. E. Roach and Daniel Barbier

Abstract--The brightness of the night sky in the Mojave Desert has been systematically measured with a recording photoelectric photometer of recent design. The instrument automatically covers the entire sky in a series of horizon to horizon sweeps in eight different azimuths. Observations are alternately made through two interference filters one of which includes a characteristic emission of the upper atmosphere and the other excludes the emission and serves as a control. In the interpretation of the data in terms of the heights to the emitting layers an attempt has been made to allow for the asymmetrical brightness of the night sky for various azimuths. For four nights in the winter of 1948-1949 we find for OI 5577 a height to the emitting layer of 110 km and for three nights during the same period for NaI 5893 a height of 310 km.

Introduction--One of the methods of probing the upper atmosphere is by the study and analysis of the radiations of the night sky. The light includes integrated starlight, zodiacal light, aurora, galactic light, and emissions from the Earth's upper atmosphere. Spectrographic investigations have shown that the principal upper atmosphere emissions in the visible spectrum are as listed in Table 1. For a detailed compilation of the bands of O₂ and N₂ in the night sky see SWINGS [1948, p. 162], and for a list of lines in the near infrared see MEDNEL [1948].

Table 1--Characteristic night emissions for the upper atmosphere
in the absence of a polar aurora

Wavelength	Source
A	
10,440	(0,0) transition of first positive system of N ₂
6560	Broad feature; may be blend of several bands of the first positive system of N ₂
6363 } 6300 }	Forbidden transitions of OI; 1D - 3p
5893	Sodium D-lines
5577	Forbidden transition of OI; 1S - 1D
3084-3832 (17 bands)	Herzberg system of O ₂
3338-4535 (14 bands)	Vegard-Kaplan system of N ₂

The spectrographic study of night sky emissions calls for long exposures (several hours) even with rapid instruments, making investigations requiring high time resolution impossible. Photoelectric methods of measuring faint emissions have the advantage of rapid response but because of the wide spectral bands of sensitivity of photoelectric surfaces a sacrifice of spectral resolution usually accompanies the gain in time resolution. A happy solution would be a monochromator with photoelectric pick-up. In the present report we have approached the ideal solution by using interference type filters to transmit narrow bands, which include the emission under study, in conjunction with a photoelectric photometer. The transmission bands are of the order of 150 Angstroms in width at half intensity so are not even approximately monochromatic but we have adopted methods of analysis which make allowance for this.

Results of the analysis of seven nights of observation with our equipment are included in this report.

The photometer--A detailed description of the photometer will appear elsewhere [MARLOW and PEMBERTON, 1949]. A functional description will be given here. The sensitive element is an RCA-1P21 photomultiplier tube which receives the light from a two-element lens of four-inch aperture and four-inch focal length. A diaphragm in the focal plane permits the transmission of a patch

of sky approximately two degrees by ten degrees. A chopper in the converging light beam gives a 30-C/S signal. The initial photoelectric current is multiplied within the tube by a factor of the order of one million and is further amplified by a two-stage a.c. amplifier of the negative-feedback type of high stability and linearity, the current amplification of which is about 10^5 for the maximum setting. The sensitivity is controlled by a choice of nine grid-leak resistors in the second stage, varying by a factor of two from one to another. A recording meter having a range from zero to one millampere is used to record the amplified current.

The telescope of the photometer is on an alti-azimuth mounting. By remote control it can be trained on any part of the sky; it can be made to sweep from horizon to opposite horizon and return with indefinite repeats for any fixed azimuth; or it can be preset to cover the sky in a series of eight horizon to horizon sweeps, the azimuth changing by $22\frac{1}{2}^\circ$ at the end of each sweep. A single sweep requires four minutes overall and a series of eight sweeps, or a survey, takes 32 min. On occasion we have made twenty or more surveys in a single night extending from astronomical twilight to astronomical dawn.

In Figure 1 is shown a view of the photometer proper. Figure 2 shows a typical tracing in which observations are made alternately through two different filters in four second intervals. In the example shown the higher readings are made with a filter that includes the D-lines and the lower reading corresponds to a spectral region devoid of prominent night sky radiations.

Observations--On seven nights as shown in Table 2 observations have been made which lend themselves to analysis. All observations were made at an observing station located at Cactus Peak

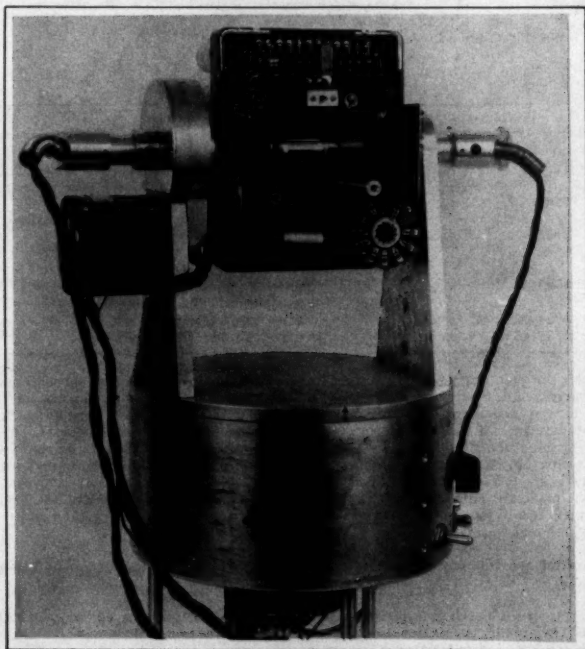


Fig. 1--Photometer with back plate removed showing 1P21 photomultiplier tube

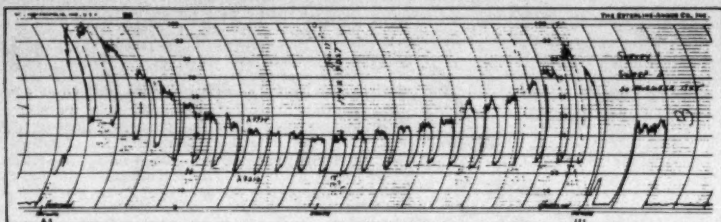


Fig. 2--Typical tracing from photometer; larger readings are with an interference filter with maximum transmission at 5935A including sodium D-lines; smaller readings are with a control filter with maximum transmission at 5210A

Table 2--Log of observations

Night of	Control filter	Night sky filter	Number of sky surveys
Nov. 27, 1948	5210	5577 (OI)	10
Nov. 28, 1948	5210	5577	17
Dec. 1, 1948	5210	5577	17
Jan. 31, 1949	5210	5577	15
Nov. 29, 1948	5210 (NaI)	5893 (NaI)	20
Nov. 30, 1948	5210	5893	19
Dec. 28, 1948	5210	5893	21

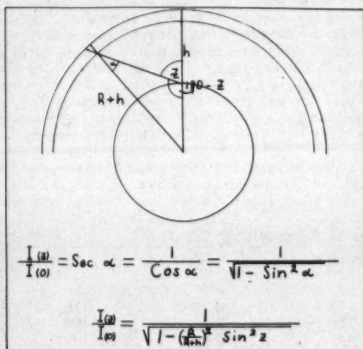


Fig. 3--Emission from thin layer in the upper atmosphere, lower atmosphere ignored

value greater than unity at the horizon which variation is a function of the assumed height. The extinction caused by the lower atmosphere becomes increasingly important with increasing zenith distance, actually causing the observed intensity of the emission to decrease near the horizon, going through a maximum at a zenith distance between about 70° and 85° depending on the height to the emitting layer. The scattering caused by the lower atmosphere increases with zenith distance compensating for a part of the extinction but not changing the general shape of the curves. A family of theoretical curves is shown in Figure 4. In principle the determination of the height to an emitting layer consists of matching the observations and the theoretical curves for optimum agreement.

near the northwest corner of the Naval Ordnance Test Station (latitude $36^\circ 04' 41''$ N; longitude $117^\circ 48' 54''$ W; elevation 5415 ft). The location is well away from most artificial illumination although the lights of the base are visible on the southeastern horizon.

Heights to emitting layers--For the purpose of estimating the height to the portion of the upper atmosphere emitting a particular radiation it is necessary to interpret the variation of the intensity of the radiation from the zenith to the horizon. If there were no lower atmosphere to absorb and scatter the light and, assuming an optically thin layer, the variation would be given by

$$I(z)/I(0) = 1/\sqrt{1 - R^2 \sin^2 Z / (R+h)^2} \dots (1)$$

in which $I(z)$ is the radiation intensity for a given zenith angle and the other symbols have the significance indicated in Figure 3, which assumes that there is no lower atmosphere to scatter and absorb light, and the layer is optically thin. This ratio increases from unity at the zenith to a finite

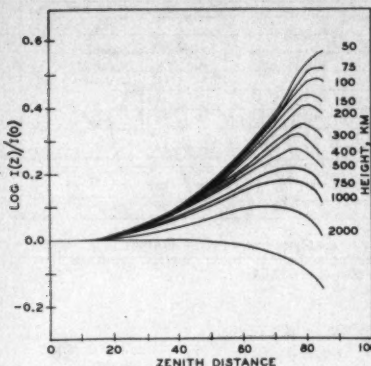


Fig. 4--Theoretical variation of intensity with zenith distance for various assumed heights including effect of extinction and scattering; extinction coefficient τ is assumed to be $0.05 + \text{ozone}$

than fitting the data and theory at all zenith distances. A typical result obtained with this procedure is shown in Table 3 for the first survey of November 30, 1948, which was made with sodium D light.

The striking feature of the tabulation is the very wide variation in the deduced heights, listed in the last column, for the various azimuths. It is difficult to believe that such changes in height can represent physical reality and we have examined the alternative that a modification of the interpretation is necessary. One of the basic assumptions in the derivation of Eq. (1) is that the emitting layer is of constant thickness, and hence brightness as seen from the center of the Earth and that the increase of brightness toward the horizon is due to an increase in the projected thickness as seen by the observer from the surface of the Earth. If, on the other hand, the observer is looking at regions of the sky for which the intrinsic thickness of the emitting layer is different the equation does not apply.

With this possibility in mind we have plotted, for each survey, intensity isophotes at zenith distance 80° , as in Figure 5, where the numerical values refer to galvanometer readings. The isophotes may be interpreted as iso-thickness lines in which case true values of height are obtained only for

from that of the upper atmospheric emission. Since the photosensitive surface has a strong wavelength dependence it is not possible to make the subtraction directly. Furthermore we have found it convenient in working with the sodium D-line filter to reduce the aperture of the control filter (5200A) in order to compensate for the large difference in the sensitivity between the two wavelengths (the 1P21 tube is approximately four times as sensitive at 5200A as at 5900A). In the case of the oxygen line at 5577A both filters were used with full opening. In view of these complications it is necessary to determine an empirical factor to adjust the two filters to the same effective sensitivity. We have assumed that the background radiation has an energy distribution corresponding to a GO star. Each filter was calibrated by systematic observations on bright stars using the data of KEINLE, STRASSL and WEMPE [1938, System S, Tab. 15, p. 265] to reduce a star of any particular spectral class to GO.

The residual remaining after subtracting the intensity through the control filter from that through the emission filter is assumed to correspond to the intensity of the emission line. For the first approximation of the height to the emitting layer it is convenient to use the ratio of intensities at zenith distances 80° and 0° rather

Table 3--Survey 1: November 30, 1948: sodium D light

Azimuth	$I(\text{zenith})$ (mean)	$I(80^\circ)$	$I(80)/I(0)$	$\log [I(80)/I(0)]$	Height
0	17.7	37	2.09	0.320	360
22 1/2	17.7	39.5	2.24	0.349	300
45	17.7	45	2.54	0.406	200
67 1/2	17.7	53	2.99	0.476	100
90	17.7	51	2.88	0.460	120
112 1/2	17.7	42.5	2.40	0.381	250
135	17.7	50	2.82	0.451	135
157 1/2	17.7	54	3.05	0.484	95
180	17.7	49	2.76	0.442	150
202 1/2	17.7	58	3.28	0.516	70
225	17.7	55	3.11	0.493	90
247 1/2	17.7	53.5	3.02	0.481	100
270	17.7	49	2.76	0.442	150
292 1/2	17.7	45	2.54	0.405	200
315	17.7	44	2.48	0.396	220
337 1/2	17.7	40	2.26	0.354	295

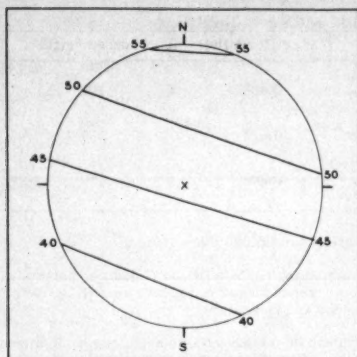


Fig. 5--Plot of isophotes for Survey 1; November 30, 1948; zenith distance, 80°; sodium D light

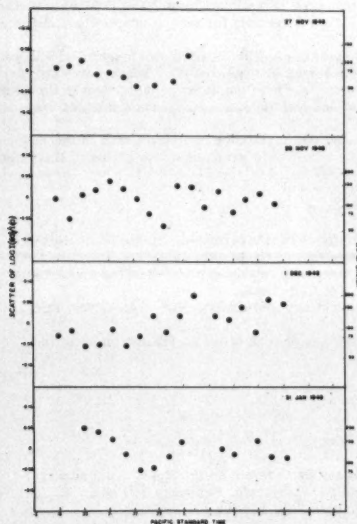


Fig. 6--Scatter of $\log I(80)/I(0)$ for OI 5577 throughout the night; corresponding scatter in deduced heights are shown on the scale at the right

Table 4--Summary of height determinations, OI 5577

Night of	$\log I(80)/I(0)$	Deduced height
		km
Nov. 27, 1948	0.486	70
Nov. 28, 1948	0.444	115
Dec. 1, 1948	0.450	110
Jan. 31, 1949	0.427	130
Mean	0.452	110

Table 5--Summary of height determinations, NaI 5893

Night of	$\log I(80)/I(0)$	Deduced height
		km
Nov. 29, 1948	0.357	280
Nov. 30, 1948	0.383	240
Dec. 28, 1948	0.295	440
Mean	0.345	310

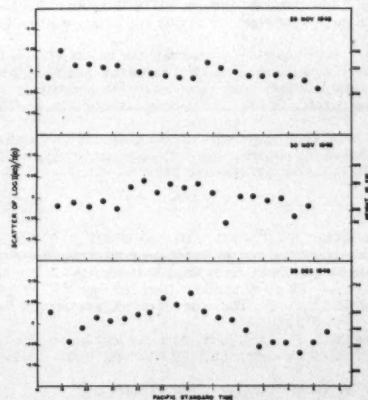


Fig. 7--Scatter of $\log I(80)/I(0)$ for NaI 5893 throughout the night

sweeps parallel to the lines, and meaningless values are obtained if observations cut across the isophote lines. With this interpretation only one sweep from horizon to horizon is valid for each survey of eight sweeps. For example, referring to Figure 5, the sweep from azimuth $112 \frac{1}{2}^\circ$ to $292 \frac{1}{2}^\circ$ most nearly parallels the isophotes. From Table 3 it is seen that the heights for these two azimuths are 250 km and 200 km which are in satisfactory agreement. We have adopted the above

Table 6--Effect of starlight on deduced heights

Item	I(0)	I(80)	Log [I(80)/I(0)]	Deduced height km
True intensity (no starlight)	20	58	0.463	100
Observed intensity (including starlight)	22.5	59.5	0.423	125
Observed intensity (Milky Way in zenith)	30	59.5	0.298	350

procedure for all our records, the results of which are recorded in Tables 4 and 5.

In Figures 6 and 7 we show the variation of observed log [I(80)/I(0)] and of deduced heights with time for the seven nights. For the sodium D-lines the trends appear to follow a smooth course. For the oxygen green line the scatter seems to be more of a random nature.

We call attention to the nature of the errors that can be introduced into height determinations if the observations are not corrected for the presence of non-atmospheric components in the light of the night sky. To illustrate the difficulty, reference is made to Table 6 in which three cases are presented. In the first case it is assumed that all the light originates in the upper atmosphere at a height of 100 km. If normal integrated starlight is then added to the intensities and not allowed for the deduced height is 125 km. If, in an extreme case, the Milky Way is in the zenith the deduced height is 350 km. Similar errors will be introduced by the presence of zodiacal light. The two color method of analysis presented in this report automatically makes allowance for non-atmospheric components.

It is possible to calibrate the photometer by observations of stars of known brightness and color. Such a calibration yields a value for unit deflection in terms of ergs/sec cm² which, for monochromatic radiation, can be converted to transitions/sec cm². From the average deflection in the zenith we find for OI 5577, 6×10^8 transitions/sec cm²; and for NaI 5893, 2×10^8 transitions/sec cm².

Acknowledgments--It is a pleasure to acknowledge the assistance of Helen Pettit in the reduction of the observations. The project is supported by a research grant from the Office of Naval Research, contract NR-082-045.

References

- KIENLE, H., STRASSL, H., and WEMPE, J., Die relative Energieverteilung im kontinuierlichen Spektrum von 36 Fundamentalsternen, *Zs. Astrophys.*, v. 16, p. 201, 1938.
- MARLOW, DOUGLAS, and PEMBERTON, J. C., An automatic scanning and recording photometer for night sky studies, *Rev. Sci. Inst.*, v. 20, pp. 724-728, 1949.
- MEINEL, A. B., The near infrared spectrum of the night sky and aurora, *Pub. Astro. Soc. Pac.*, v. 60, p. 373, 1948.
- SWINGS, P., Spectra of night sky and aurora, in *The atmospheres of the Earth and planets*, (ed. G. P. Kuiper), Univ. of Chicago Press, 1948.
- U. S. Naval Ordnance Test Station^a,
Pasadena and Inyokern, California,
August 5, 1949
- ^aD. B. on leave from Institut d'Astrophysique, Paris.

(Manuscript received May 3, 1949; presented at the Symposium on the Upper Atmosphere, Twenty-Third Regional Meeting, Los Angeles, California, February 5, 1949; open for formal discussion until July 1, 1950.)

SODIUM IN THE UPPER ATMOSPHERE

Daniel Barbier and F. E. Roach

Abstract--Observations of the emission of the sodium D lines in the late twilight are interpreted on the assumption that the physical cause of the radiation is resonance excitation of the sodium atoms by sunlight. The distribution of neutral sodium atoms in the region 200 to 600 kilometers is found to follow the law $n = 1.4 e^{-h/250}$ atoms/cm³ where h is the height above the Earth's surface in kilometers. The apparent scale height of 250 km is much greater than that of the lower atmosphere (about ten kilometers) suggesting either that the upper atmosphere decreases in density much more slowly than the lower atmosphere or that sodium is of extra-terrestrial origin.

In an earlier paper [ROACH and BARBIER, 1950] referred to as Paper 1, we have reported a study of the D lines of sodium in the light of the night sky for November and December 1948, leading to the conclusions that the emitting atoms are concentrated at an average effective height of 310 km and that the average intensity of the light in the zenith corresponds to 8×10^7 transitions per second per cm² column. The value for the effective height is surprising especially in contrast with a corresponding figure of 110 km for the light from the forbidden oxygen transition at 5577 Å. Because of the high intrinsic sensitivity of the sodium D lines it is likely that their study will be especially useful in the analysis of the upper atmosphere. In this paper we present data obtained with the same photometer described in Paper 1 which give further information on the distribution of sodium atoms in the ionosphere.

The observations--Astronomical twilight is considered to end when the Sun is 18° below the horizon. Our records have shown that there is a late twilight enhancement of the D lines observable in the west in the evening when the Sun is between 18° and 40° below the horizon, and symmetrically in the east in the morning sky. The nature of the enhancement is shown in Figure 1 in which the sodium-D intensity is plotted as a function of azimuth at a zenith distance of 80° for the first four surveys of the night of November 30, 1948. The variation of intensity when the Sun is depressed by 48° is typical of the night sky for several later surveys and is the type is asymmetry that is considered in the analysis of the night sky presented in Paper 1. The broad maximum near the north (azimuth = 180°) persisted until about midnight with a gradual shift to the east of north. The maximum between 70° and 90° azimuth appears with diminishing intensity as the Sun sinks from $\theta = 27^\circ$ to $\theta = 41^\circ$ and it is this type of variation which is the subject of the present paper.

The enhancement is definitely not associated with the zodiacal light. Our two color method of analysis (refer to Paper 1) automatically subtracts the zodiacal light. If, however, there were a systematic error in our method such that the control color (5210Å) was under-corrected there might result a pseudo enhancement. That this is not the cause of our observations is proven by two facts, namely: (1) The effect has never been observed for the oxygen line 5577 for which the same method of analysis has been used. (2) The azimuth of the maximum agrees well with the azimuth of the Sun at the time of the observation and is definitely not in agreement with the azimuth of the ecliptic. The ecliptic is inclined sharply to the horizon during the winter season in mid latitudes which makes it possible to apply a critical test. Collecting the data for zenith distance 80° we find the following for seven evening and twelve morning observations: Evening, A - A (Sun), - 3.7, A - A (Zodiacal light), + 21.9; Morning, A - A (Sun), + 0.7, A - A (Zodiacal light), - 15.9.

We have adopted the point of view that the enhancement is a late twilight (or early dawn) effect caused by the illumination of the upper atmosphere by the Sun. In Table 1 are collected the observations for six cases. The symbols have the following meanings: Z, zenith distance of the observation; θ , angular depression of the Sun below the horizon; h_0 , the height in the atmosphere to the grazing ray of the Sun (see Figure 2); I, intensity of the enhancement in units of galvanometer deflections; I', the intensity of the enhancement referred to the zenith (by multiplication by $\cos \alpha$) and adjusted to $I = 10$ for $\theta = 30^\circ$. The correction factors used in adjusting I' to $I = 10$ at $\theta = 30^\circ$ were obtained from smoothed working plots of I versus θ for each night and are listed in Table 2.

In Figure 3 is shown the relation of I' to h_0 . The observations are compared with the curve

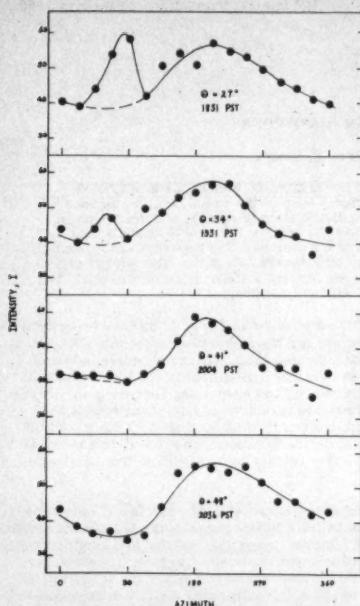


Fig. 1--Variation of intensity of sodium with azimuth ($0^\circ = \text{South}$) for the evening of November 30, 1948; zenith distance equals 80°

Table 1--Log of observations, 1948

Date	Time PST		Z	θ	h_0	I	I'
1948	h	m		$^\circ$	km		
Nov. 29	18	27	80	22	230	16	5.6
	19	01	80	28	340	10	3.3
	19	35	80	35	510	6	2.2
	20	07	80	41	680	0	0
Nov. 30	2	26	80	52	1100	0	0
	2	58	80	45	810	8	2.6
	3	31	80	38	590	12	3.5
	4	04	80	31	410	11	2.8
	4	37	80	25	280	16	3.8
Nov. 30	5	09	80	19	180	16	3.2
	18	51	80	27	320	22	4.2
	18	51	70	27	420	6	2.6
	19	31	80	34	480	10	1.8
	20	04	80	41	690	2	0.8
Dec. 1	20	36	80	48	940	0	0
	2	30	80	49	960	0	0
	3	09	80	43	750	5	1.3
	3	32	80	38	590	11	2.7
	4	15	80	29	360	12	3.7
Dec. 28	4	15	70	29	470	9	2.7
	4	47	80	23	250	18	4.2
	4	47	70	23	320	13	3.8
	4	47	60	23	370	3	1.1
	18	34	80	21	210	24	6.2
Dec. 28	19	18	80	30	380	12	3.7
	19	50	80	36	540	0	0
	3	54	80	37	560	0	0
Dec. 29	4	27	80	31	410	8	3.5
	4	59	80	24	260	11	4.2
	5	31	80	18	170	28	9.4

$$I' = 14e^{-h_0/250} \dots \dots \dots (1)$$

Equation (1) will be adopted as representing empirically the variation of the intensity of integrated sodium light with height to the grazing layer.

Interpretation of the observations--The end result of this investigation is the relation of sodium density in atoms per cm^3 to height above the Earth's surface. The fundamental physical assumption which we make is that the emission is a resonance phenomenon activated by solar radiation.

The first step in the analysis was to calibrate the galvanometer deflections in terms of absolute units. For standard light sources we used stars of known brightness and color many of which gave deflections on our records in the course of a night's run. It has been found that unit deflection under the conditions of our observations corresponds to: 1.04×10^{-9} ergs/ cm^2 sec square degree, or 1.28×10^7 transitions/sec in a column of one square centimeter cross section. Thus (1) may be written

$$\eta = 1.8 \times 10^8 e^{-h_0/250} \text{ transitions/cm}^2 \text{ sec} \dots \dots \dots (2)$$

The calculation of the number of sodium atoms in a one square centimeter column is based on the resonance assumption that the number of atomic transitions from the ground level of sodium n to the upper level m is equal to the number of transitions from m to n . If the density of the solar radiation is u_ν then

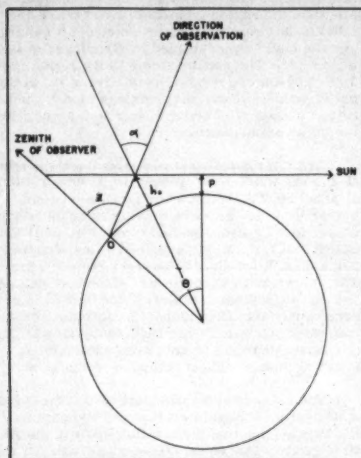


Fig. 2--Height h_0 to the grazing ray of the Sun; because there is significant ozone absorption at 5893A, the effective surface of the Earth is the top of the ozone layer at a distance p from the actual surface

Table 2--Correction factors

Date	Time	Correction factor
Nov. 29	Evening	10/9.5
Nov. 30	Morning	10/13
Nov. 30	Evening	10/15
Nov. 31	Morning	10/13.5
Dec. 28	Evening	10/11
Dec. 29	Morning	10/15

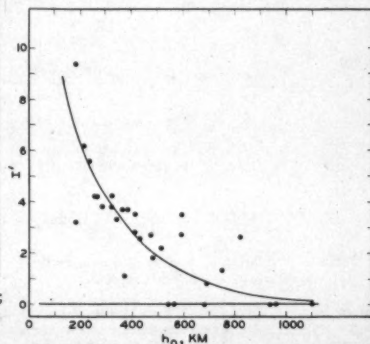


Fig. 3--Variation of I' (reduced intensity) with h_0

$$\eta = u_p g_m B_{mn} N_n / g_n = Q N_n \dots \dots \dots (3)$$

where N_n is the number of sodium atoms in the ground level, n , g_m and g_n are the statistical weights of states m and n respectively, and B_{mn} is the Einstein coefficient of induced absorption, which for the sodium D-lines is known to be 2.32×10^{20} . For u_p , at the Earth's distance from the Sun we find a value of 7.86×10^{-21} assuming that the intensity of solar radiation in the center of the D-lines is one tenth that of the adjacent continuum.

Thus we find $Q = 5.5$ and $N = 0.18 \eta$ and

$$N = 3.4 \times 10^7 e^{-h_0/250} \text{ atoms/cm}^2 \text{ column} \dots \dots \dots (4)$$

The number of atoms per cm^3 is found by differentiating N with respect to h_0 giving

$$n = -(dN/dh_0) \times 10^{-5} = 1.4 e^{-h_0/250} \text{ atoms/cm}^3 \dots \dots \dots (5)$$

Discussion of results--The relation of $\log n$ (sodium) to height h_0 as determined in this study is plotted in Figure 4 together with a similar determination for lower altitudes as given by BARBIER [1949]. For comparison, the values of the log of the total number of particles in the atmosphere as given by GRIMINGER [1948, Tables 14 and 27], are separately plotted. For convenience the values of the logarithm of the latter are reduced by 12. The approximate agreement of the observations for sodium in the regions from 70 - 100 km with the total number of molecules indicates that sodium atoms constitute about 10^{-12} of the particles in this region. Finally a comparison of a recent determination by ELVEY [1947, p. 19] of the variation with height of the intensity of OI 6300 is shown.

A striking feature of the deductions of this study for the region from 200 to 600 km is that the slope of the curve of the relation of $\log n$ to h_0 is very much less than for the region from 70 - 100 km and also than for the curve of the atmosphere given by Griminger. Two alternative explanations

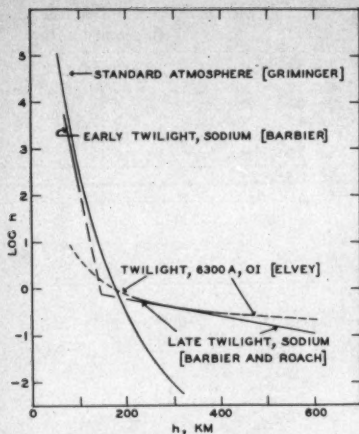


Fig. 4--Variation of density of sodium with height above the Earth's surface

lines in the night sky spectrum by the assumption of a patchiness in the distribution of sodium in the solar system. No direct knowledge of the amount of inter-planetary sodium is available but it is known that the average density of interstellar sodium is about 5×10^{-9} atoms/cm³ [SPITZER, 1948, p. 276]. To account for the approximately one atom/cm³ deduced by this study in the upper atmosphere would call for a marked increase in density of interplanetary sodium over that in interstellar space.

Comparison of sodium emission in the night sky and the late twilight--The results of this paper and of Paper 1 are shown in Table 3.

Table 3--Comparison of sodium emission in the night sky and the late twilight

Item	Night sky	Twilight
Mean effective height	310 km	
Transitions/cm ² sec	2×10^8	
Density at 310 km		0.8 atoms/cm ³
Excitation mechanism	Unknown	Resonance (sunlight)

An elementary calculation shows that, if the distribution of sodium atoms is as indicated in Figure 4, an effective height of 310 km during the night precludes the possibility that the region from 70 - 100 km contributes to the light. If the distribution of atoms follows an exponential law we have for the mean effective height h , if h_1 is the lower limit,

$$\bar{h} = \frac{\int_{h_1}^{\infty} nh dh}{\int_{h_1}^{\infty} n dh} = \frac{\int_{h_1}^{\infty} e^{-h/H} h dh}{\int_{h_1}^{\infty} e^{-h/H} dh} = h_1 + H \dots \dots \dots (6)$$

In the region from 70 - 100 km the scale height is about eight kilometers. If a lower limit is taken in this region it is, therefore, impossible that there will be any effective contribution from the 300 - km region. If there is a rapid change of scale height in the 100-km region it would be possible to reconcile a mean effective height of 300 km with a scale height of 250 km without including the region from 70 - 100 km as a contributor to the sodium light in the night sky. Thus the twilight and night sky data can be reconciled if it is assumed that the sodium atoms below 100 km do not contribute to the light of the night sky.

of this effect are suggested: (1) The sodium atoms in the region from 200 - 600 km are an index of the distribution of the molecules in general and the distribution adopted by Griminger is in error. (2) The sodium atoms in the region from 200 - 600 km are not representative of the atmosphere as a whole and the change of slope is indicative of an extra-terrestrial source of sodium in the upper atmosphere.

The first hypothesis requires a scale height of 250 km which corresponds to a temperature of about 6000°K. Such a temperature is much higher than the values deduced from scale heights determined by radio studies of the F layer [PENN-DORF, 1946, p. 331], the highest value reported being 2000°K for the region from 200 - 300 km. The approximate agreement of slope between our results for sodium and Elvey's for OI 6300 is not necessarily significant since the forbidden oxygen transition has a mean life sufficiently long to permit recombinations by collision, especially at lower altitudes, without emission of radiation.

The second hypothesis implies that the Earth is sweeping through interplanetary sodium clouds and thus augmenting the natural supply in the Earth's atmosphere. One of the attractive features of this hypothesis is the possibility of explaining the seasonal variations in the intensity of the sodium-D

It is of interest to calculate the order of magnitude of the number of quanta per sec per atom in the night sky. The night sky light corresponds to 2×10^8 transitions/sec cm^2 column. The total number of atoms contributing to the light may be estimated by assuming 100 km as the lower limit and a distribution according to $n = 1.4 e^{-h/H}$ atoms/ cm^3 which gives $\int_{100}^{\infty} n \, dh = 1.7 \times 10^7$ atoms in a one square centimeter column. Thus the number of quanta per second per atom is about 12.

Acknowledgment--This project has been supported by a research grant from the Office of Naval Research, project NR-082-045.

References

- BARBIER, DANIEL, L'émission crépusculaire des raies de Na et OI, Ann. Geophys., v. 4, fasc. 3, pp. 193-210, 1948.
- ELVEY, C. T., Report of Gassiot Committee Conference of July 1947, Physical Society of London.
- GRIMINGER, G., Analysis of temperature, pressure, and density of the atmosphere extending to extreme altitudes, Report R-105, November 1, 1948.
- PENNDORF, R., The temperature of the upper atmosphere, Bull. Amer. Met. Soc., v. 27, p. 331, June 1946.
- ROACH, F. E., and BARBIER, DANIEL, The height of emission layers in the upper atmosphere, Trans. Amer. Geophys. Union, v. 31, pp. 7-12, 1950.
- SPITZER, LYMAN, JR., The distribution of interstellar sodium, Astrophys. J., v. 108, p. 276, 1948.
- U. S. Naval Ordnance Test Station^a,
Pasadena and Inyokern, California,
May 16, 1949

^aD. B. on leave from Institute d'Astrophysique, Paris.

(Manuscript received May 16, 1949; presented at the Symposium on the Upper Atmosphere, Twenty-Third Regional Meeting, Los Angeles, California, February 5, 1949; open for formal discussion until July 1, 1950.)

AURORA SPECTRA SHOWING BROAD HYDROGEN LINES

C. W. Gartlein

Abstract-- The best spectra of the aurora taken since 1939 with the two prism spectrograph having camera lens ten cm focal length and $F/1.65$ aperture show lines, approximately five Å broad, within two to five Å of the positions of H_{α} , H_{β} and H_{γ} . Large scale microphotometer tracings separate these lines from the various bands of N , and the identification as hydrogen seems established. Many spectra taken on the time sequence spectrograph, aperture $F/0.8$, show that these lines appear most strongly preceding and during an outburst of aurora. This is in support of Eckersley's theory of ionosphere disturbances. Thus, there is evidence to indicate that the hydrogen is of solar origin and a primary cause of some aurora outbursts and magnetic storms.

The National Geographic Society - Cornell University Study of Aurora has used a precision spectrograph at Ithaca, New York, to record the spectra of all the stronger auroras since 1939. This spectrograph uses two prisms, a long focus collimator and camera $F/1.65$ of 100 mm focus. Eastman spectroscopic plates 103 C were used until 1944, when we changed to 103AF plates to give better red sensitivity and speed. The graininess of the plates as well as the desire to record faint bands requires the use of a wide slit so the resolving power on the final spectrum plates seldom exceeds 500.

The usual well known features of auroral spectra regularly appear. The second green line appears resolved into oxygen bands at 5296 Å and 5250 Å and nitrogen negative bands at 5228 and 5145 Å as well as the sharp forbidden NI lines at 5199 Å.

In addition to these features, lines appear near 6563, 4861 and 4340 Å. The first two have been observed previously by L. Vegard and others who have identified them as hydrogen lines. We agree with this but for stronger reasons than those usually given. The wavelength measurements can only be made with a precision of one to two ångströms and this is not precise enough for positive identification. In addition these three lines rise and fall in intensity together and not in step with other lines. They are strongest during great auroras and especially during the building up of the display, as early in the display of September 18, 1941. Comparison of our twelve best spectra shows that the hydrogen lines can be either strong or weak for a given intensity of lines of NI, NII or the various bands of nitrogen. This is strong evidence that these three lines belong to the same element or constituent. Another argument for this identification is that no other lines or bands have been discovered which could be expected to give only the three lines.

The possibility that the line at 6563 Å, which always appears superposed on positive bands of nitrogen, is really a blend of the forbidden lines of NII at 6583 and 6547 Å can be eliminated for two reasons. The 6563 line is not that broad and it is often strong when the NII lines at 5676 and the NI line at 5199 Å are weak. Thus we conclude the three lines are hydrogen.

Critical examination of the H_{α} , 4861, and H_{γ} , 4340, lines shows them to be broader than the lines believed to be single atomic lines. Microphotometer traces were run of various spectrograms and all show approximately the results given below from plate 655, taken March 23-24, 1946 with an exposure of about four hours.

Figure 1 is a copy of parts of this microphotometer trace with intensity scale at the left. The arrows in Figure 1 mark the half intensity points of all the lines. At these arrows the width of lines of monochromatic radiation are those given by the geometrical image of the spectrograph slit, which is the same for all wavelengths. We note that radiations 5199 Å of NI and 4368 Å of OI are the narrowest. The width of 5676 Å and 5003 Å is greater and both are known to be close multiple lines. The hydrogen lines are very wide compared to these four radiations.

To find the actual wavelength spread of the hydrogen lines we subtract the width of $\lambda 5003$ at a given density, (height on Figure 1) from the width of the hydrogen at the same density. This procedure is incorrect but gives a minimum value for the line widths. These excess widths are plotted in Figure 2 for both hydrogen lines, giving about 16 Å for H_{β} and 14 Å for H_{γ} . The width at half

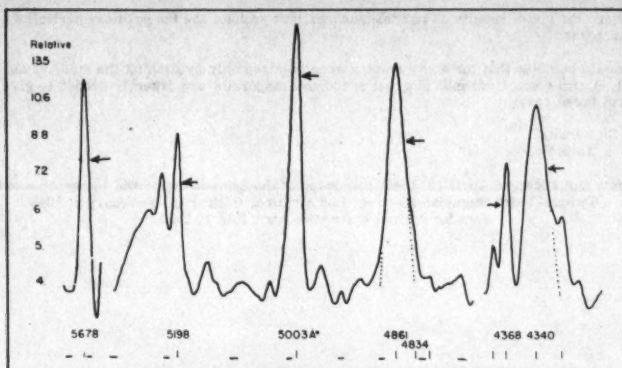


Fig. 1--Part of a microphotometer plot of the intensity of the spectrum line versus the wavelength

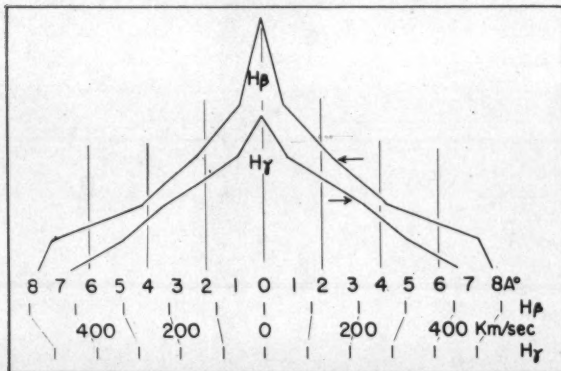


Fig. 2--Plot of the intensity of two hydrogen lines versus angstrom width and line of sight velocity

intensity is marked by arrows. The above procedure is so crude that the shapes of the curves cannot be analyzed to have any meaning.

The values of pressure, temperature, magnetic field or electric field required to produce such broadening are so great that we know they cannot occur in the upper atmosphere. Thus we believe the broadness of these lines can be ascribed only to Doppler broadening due to line of sight motion when the atoms are radiating. These possible velocities are indicated in Figure 2.

It has been postulated that protons from the Sun penetrate the atmosphere in the production of ionospheric disturbance and cause much ionization. This would presumably occur strongly during and before great outbursts of the aurora.

The spectrograms taken with our F/0.8 patrol spectrograph show the spectrum spread out in time. The hydrogen lines are visible on these plates in most auroras but are especially strong just before and during an outburst of aurora, as would be expected by the Eckersley theory. Thus we

must regard the above results as partial evidence that protons are the primary particles exciting certain auroras.

It should be noted that the above results were obtained only by pushing the study of our plates to the limit. Larger spectrographs of great speed and dispersion are urgently needed to give plates to confirm these results.

Cornell University,
Ithaca, New York

(Manuscript received April 19, 1949; presented at the Symposium on the Upper Atmosphere,
Twenty-Third Regional Meeting, Los Angeles, California, February 5, 1949;
open for formal discussion until July 1, 1950.)

STRONG PERMITTED OI AND NI LINES IN THE INFRARED AURORAL SPECTRUM

A. B. Meinel

Abstract--Observations of the near infrared spectrum of the aurora show the presence of strong permitted lines of oxygen and nitrogen and enhancement of the first positive nitrogen bands. The newly observed atomic lines provide information about the relative numbers of oxygen and nitrogen atoms and the variation of excitation with energy level. Concurrent observations of the night-sky spectrum show conclusively that the telluric bands appear in absorption. Emission is observed however from the subordinate bands of the atmospheric oxygen band.

Introduction--The nature of the infrared radiations from the upper atmosphere has been the subject of considerable attention during the last few years. During the summer of 1948 a series of spectrographic observations, intended to survey the infrared spectrum of the night sky and aurora with a relatively high dispersion, was initiated at Lick Observatory.

The spectrograph consisted of a large transmission replica grating, kindly loaned by R. W. Wood, and a flat-field Schmidt type camera of an effective speed of F/1. No collimator was necessary since the slit was placed at a large distance from the grating. The grating is 110 mm by 165 mm, has 7500 lines per inch, and has a maximum energy concentration of the order of 80 per cent in the first order at about 8000Å. The camera has a focal length of 140 mm, producing a dispersion of 250Å/mm in the first order. Five zenith distances, distributed along the meridian from two degrees above the northern horizon, were photographed simultaneously by means of a set of Dove prisms placed in front of the slit.

A preliminary seven hour exposure taken on a hypersensitized Eastman 1-N emulsion in July, 1948, with an equivalent slit width on the plate of 50 microns, showed a large number of distinct radiations to the limit of the plate sensitivity. This indicated that the bands observed under extremely low dispersion by SLIPHER [1933] were in fact very complex aggregations of radiations. Four exposures up to 32 hr duration subsequently were taken with an equivalent slit width of 30 microns. A table has been published [MEINEL, 1948] which gives the wavelengths of the numerous emission features to an accuracy of about one angstrom. On August 7-8, 1948, during the first night of an exposure, there appeared a faint diffuse aurora to the north, which produced a strong spectrum, radically different from that of the night sky. Figure 1 is a reproduction of the two types of spectra. It should be noted that, in preparing the reproductions, only one zenith distance from the set of five zenith distances represented on each plate was selected and widened. As a result of the widening, the reproduction shows many spurious faint lines which are due solely to random fluctuations in the silver grain distribution over the short width of the spectrum on the original plate.

Auroral spectrum--The most striking feature of the auroral spectrum is the appearance of a group of very intense radiations near 7700Å. The first three appear to be of molecular origin, with the radiations at 7688Å, 7717Å, and 7746Å coinciding with the three maxima of the (2,0)

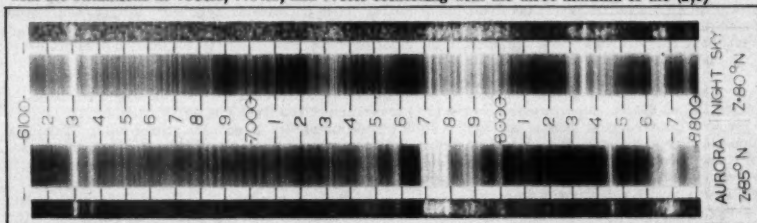


Fig. 1--The infrared spectrum of the night sky and aurora taken with a grating spectrograph

numbers of oxygen and nitrogen atoms which are in the excited states. At the present time no absolute intensities have been determined, so that we can obtain only relative numbers.

If we arbitrarily equate the sum of the f -values of the OI and NI transition arrays that arise in both cases from a $3p$ to a $3s$ electronic change, we can compute the f -numbers for each transition by assuming strict LS-coupling. Provided that we can select an OI and an NI transition having the same upper level energy, such that we may assume that the degree of excitation is the same for each, then the f -numbers should give the theoretical intensities. The two transitions that most nearly satisfy this condition are the $3^3P-3^3S^0$ OI and the $ep^4D^0-3s^4P$ NI multiplets. The theoretical ratio of the f -numbers is 0.34, while the observed ratio of intensities is 0.46. This ratio indicates that the abundance of OI is 1.5 times the abundance of NI. The fact, however, that the two multiplets have upper level energies which differ by 0.8 electron volts invalidates the assumption of equal excitation.

Since the abundances appear to be of the same order of magnitude, we shall assume tentatively that OI and NI are equally abundant in order to determine the degree of excitation for each of the observed multiplets. The ratio of the observed intensity to the theoretical intensity for each of the observed multiplets of OI and NI is shown in Figure 3. Since the intensities as computed on the basis

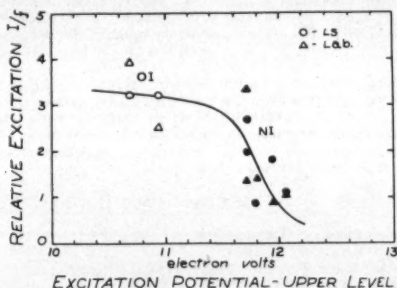


Fig. 3--Variation of the excitation with energy level for seven permitted transitions observed in the aurora

of LS-coupling from tables given by GOLDBERG [1935] do not entirely agree with the estimated laboratory intensities as given by MOORE [1945], both values are indicated. This diagram shows that a sharp drop occurs in the degree of excitation near 12 volts. The shape of the curve, however, is not defined, since the combination of the points of OI and NI depends on the relative abundances in such a way that a decrease in the relative abundance of NI would shift the points for NI upward.

The large relative abundance of NI at once raises a question as to the validity of the NI identifications, since the energy required to photodissociate N_2 is considerably greater than for O_2 . As a consequence, it has been usually assumed that atomic nitrogen, if present at all in the upper atmosphere, must be in very small amounts. Therefore, unless predissociation can play an important role in the production of atomic nitrogen, we must only consider this identification as suggestive, pending further verification.

Night sky spectrum--From the reproduction of the night sky spectrum, the appearance of the broad absorption features caused by the lower atmosphere may easily be seen at 6900Å, 7200Å, 7600Å, and 8220Å, which correspond respectively to the Fraunhofer B, a, A, and Z bands. This shows conclusively that the telluric bands do not occur in emission as was held by Sommer and by DEJARDIN [1936]. The higher members of the atmospheric A-band system of O_2 , however, appear in emission. The emissions at 8628Å and 8659Å coincide with the two maxima of the (0,1) transition. There appear to be several other coincidences with other members of the system, each with the lower level above the zero vibrational level; however, they are considerably fainter than the (0,1) transition. The fact that the 8628Å and 8659Å emissions do not exhibit any enhancement at twilight would support this identification. All the other strong radiations show a definite enhancement at twilight.

The fact that the (0,1) transition of the oxygen A-band system is quite strong would indicate that

the (0,0) transition should be strong. The appearance of this band in absorption indicates, therefore, that the mass of O_2 below the emitting elevation is sufficient to reabsorb the radiations from this transition, even though it is a forbidden transition.

At the present time it has not been possible to make any further reliable identifications, since it is necessary to consider the synthetic profiles. This information is sometimes difficult to obtain, quite largely due to the lack of information concerning band systems in the red and infrared. In order to make a survey for band systems which might be present, a table was constructed for the origins and heads for each of the numerous known systems from N_2 , O_2 , NO , CO , and CN . This method has shown some coincidences; however, the correspondences were generally inconsistent with the expected Franck-Condon parabola. The fact that there are so many radiations representing a considerable amount of energy, which cannot be identified with known band systems, seems to indicate the need for more intensive studies, especially in the infrared region.

Photoelectric observations by STEBBINS, WHITFORD, and SWINGS [1945] indicate that there is a very strong radiation in the vicinity of 10000A, which may be due to the (0,0) band of the first positive system of N_2 . It is very important that a spectrographic observation be made of this region. In France, HERMANN, HERMANN, and GAUZIT [1942] reported spectrographic evidence for this emission; however, they have been unable to reobserve the same bands under conditions most favorable. In discussing this report, DUFAY [1943] expresses the opinion that the observation may have been in error.

In view of the importance in the excitation mechanism for the night sky spectrum proposed by SWINGS [1949] of a strong (0,0) transition for the first positive system of N_2 , with the absence of the other members with $v' > 0$, it is imperative that direct spectroscopic evidence be obtained for this region. The spectrograph which was used in the present survey is being modified to use an infrared sensitive photocell mounted behind a slit in the focal plane. It is hoped that this spectrophotometer will extend the survey of the night sky and aurora spectra to 11000A.

References

- DEJARDIN, G., *Rev. Mod. Phys.*, v. 8, p. 1, 1936.
DUFAY, J., *Pub. l'Obs. de Lyon*, III, 16, 1943.
GARTLEIN, C. W., *Trans. Amer. Geophys. Union*, v. 31, pp. 18-20, 1950.
GOLDBERG, L., *Astrophys. J.*, v. 82, p. 1, 1935.
HERMANN, L.; HERMANN, R.; and GAUZIT, J., *Cahiers de Phys.*, v. 12, p. 42, 1942.
MEINEL, A. B., *Publ. Astro. Soc. Pac.*, v. 60, p. 373, 1948.
MOORE, C. E., *Table of multiplets*, Princeton Obs., Revis., 1945.
SLIPHER, V. M., *Mon. Not. R. Astro. Soc.*, v. 93, p. 657, 1933.
STEBBINS, J., WHITFORD, L., and SWINGS, P., *Astrophys. J.*, v. 101, p. 39, 1945.
SWINGS, P., *The atmospheres of the Earth and Planets*, Kuiper, editor, p. 199, Univ. Chicago Press, 1949.

Yerkes Observatory,
Williams Bay, Wisconsin

(Manuscript received April 19, 1949; presented at the Symposium on the Upper Atmosphere, Twenty-Third Regional Meeting, Los Angeles, California, February 5, 1949; open for formal discussion until July 1, 1950.)

A REVIEW OF UPPER ATMOSPHERE RESEARCH FROM ROCKETS

Homer E. Newell, Jr.

Abstract--The first few years of research in the upper atmosphere from high altitude rockets are reviewed. The principal features of the high altitude rocket as a research tool are discussed; and results of various authors on pressure-temperature, solar spectroscopy, cosmic ray, ionosphere, and high altitude photography experiments are presented. The paper seeks to provide a perspective view of the field of high altitude rocket research today by summarizing material widely scattered throughout the literature of the past three years.

Ambient pressures have been measured up to 120 km in a number of rockets and shown to fall off roughly by a factor of 10 for each ten miles. From the pressure measurements ambient temperatures have been determined. Solar spectra down to approximately 2100 Å units have been obtained from rockets and have been partially analyzed. From the spectra obtained on October 10, 1946 the vertical distribution of ozone in the atmosphere has been determined, fixing a maximum of the layer at 25 km, with less than 0.0005 cm/km above 48 km. Cosmic ray experiments have led to a partial understanding of the nature and reactions of the primary particles and of the secondary particles above the atmosphere. Rough measurements of the effective electron density in the ionosphere indicate less than 10^4 electrons per cc below 80 km rising to 2×10^5 per cc. between 100 and 111 km. Photographs taken at high altitudes have provided pictures of extensive cloud formations for study.

Introduction--When it was first proposed to employ rockets to study the upper atmosphere, the total extent of their usefulness for the purpose was largely a matter of conjecture. Offsetting by an unknown amount the ability to propel instruments into the region of study were the rocket's payload limitations, supersonic speeds, high accelerations, varying aspect, short flight time, and self-destructive impact with the Earth after flight. The opportunity, however, to send instruments aloft was tempting indeed, and many insisted that the rocket would be eminently successful in probing the upper atmosphere. They felt that the rocket's main advantage would far outweigh the shortcomings. Now, in retrospect, it is gratifying to observe that this has, in fact, been the case. During the past three years the rocket's value as a research tool was firmly established.

From the V-2 program and more recently from the Aerobee program at White Sands, New Mexico, a number of previously unknown facts about the Earth's atmosphere and the Sun were learned. At the same time the scientist also became familiar with some of the peculiarities of the rocket as a research tool. This paper summarizes the work of the Naval Research Laboratory in this field [DURAND, 1949; KRAUSE, 1947; NEWELL, 1947, 1948; NAVAL RESEARCH LABORATORY, 1946ab, 1947ab, 1948] with occasional reference to that done by other agencies.

The rocket as a research tool--Initially German V-2's were the vehicles used to transport instruments aloft. More than twenty-five of them have carried upper air research equipment of some sort to altitudes in excess of 60 mi, with six rising to more than 100 mi. More recently the Aerobee sounding rocket came into service. This is a nineteen foot, liquid propellant, booster-launched, sounding rocket built primarily for high altitude research. With a 150-pound payload it can attain an altitude between 60 and 80 miles. Supported by Navy funds from the Bureau of Ordnance and the Office of Naval Research, the rocket was developed jointly by the Applied Physics Laboratory of the Johns Hopkins University, the Aerojet Corporation, and the Douglas Aircraft Company [VAN ALLEN and others, 1948abc]. Soon, it is hoped, the Navy Viking will enter the field. All of these rockets extend appreciably the portion of the atmosphere accessible to direct study.

Much of the effort during the first years went into the development of techniques and procedures and into learning about the significant characteristics of the rocket as a research tool. Gradually the original speculation was replaced by knowledge, until now it is possible to view the various features of the rocket in proper perspective. The principal advantage of the rocket is, of course, the altitude which it can attain. In its flight it either traverses the region under study; or, as in the case of solar ultraviolet research, it rises above light-absorbing layers in the atmosphere. In order to exploit this advantage, however, it is necessary first to overcome certain limitations, such as restrictions upon weights and sizes of experimental equipments, missile acceleration and vibration,

the difficulty of recovering photographic and other records from the missile wreckage after a flight, the relatively short flight time, the need for accurate tracking of the missile during flight, varying missile orientation, and supersonic speeds.

In the case of the V-2, which can carry a couple thousand pounds of equipment, space is a greater limiting factor than weight, and this in the past has had a larger effect in limiting the number of different experiments to go into a single rocket than it has had in restricting any single experiment. The smaller Aerobee, for which the normal payload is 150 pounds, requires more careful equipment design, but is nevertheless capable of carrying a fairly elaborate assembly. The 6g and 14g maximum accelerations of the V-2 and Aerobee are not too severe, and the elimination of undesirable vibrations is in most cases simply a matter of straight-forward engineering.

Although the problem of recovering instruments and photographic records from the missile after flight has been solved only partially, nevertheless the expedients currently employed are reasonably successful. Equipment suitably located on the rocket and appropriately protected has a sufficiently high chance of being retrieved to make the risk worthwhile.

The short flight time of a rocket has an obvious and appreciable effect on the choice of experiments to be performed. For example, it is not presently possible with rockets to make continuous measurements of the variation of atmospheric and solar parameters over extended periods of time. Moreover, it is not feasible to counter this deficiency by a long series of closely spaced flights both because of the tremendous expense and because of the fact that equipment sent aloft is generally expended.

It is important in interpreting rocket data to know the trajectory followed by the missile. The reason is plain. Data acquired on the variation with altitude of temperatures, pressures, ion densities, and solar and cosmic radiations, for example, contain whatever errors exist in the trajectory information. Because of its great importance, considerable effort is now being put on this problem, and it is hoped that with the aid of the Signal Corps and Aberdeen Proving Ground personnel, who provide the missile tracking at White Sands, sufficiently accurate data may be forthcoming.

At the present time, the Naval Research Laboratory obtains good relative altitude data from pressure measurements, by fitting a free fall trajectory to the times at which measured ambient pressures on ascent and descent are equal. If the two points at which these measurements are made are sufficiently high, the effect of the atmosphere on the trajectory may be neglected. An absolute variation of altitude may then be determined, if tracking data can provide the absolute altitude of at least one of the two equal pressure points. The overall error in kilometers, then, is that which exists in the tracking data, which at times appears to go as high as one kilometer. On the basis of a series of single counter measurements, the Applied Physics Laboratory suggests using the variation of cosmic ray intensity with altitude to determine the rocket trajectory [VAN ALLEN and TATEL, 1948b]. The procedure is similar to the pressure method just described.

For small uncontrolled rockets like the Aerobee, for which tracking is exceedingly difficult unless an appreciable fraction of the total payload is given over to a beacon, the trajectory is calculated from balloon-sonde wind data and expected missile performance. Such a trajectory may then be checked against pressure or cosmic ray measurements for consistency.

Orientation of the missile during flight appreciably influences the interpretation to be put on the results of cosmic ray, ionosphere, and pressure measurements. At the present time this difficulty is enhanced by a lack of reliable means for determining missile aspect. Both the V-2 and the Aerobee roll and precess after the end of powered flight. The roll of the V-2 is variable from rocket to rocket. The Aerobee on the other hand almost always rolls at one revolution per second. Although rate of roll is relatively easy to measure, the precessional motion is difficult to determine accurately. Photographic tracking, for example, does not often give complete records.

One of the Signal Corps' contractors (G. M. Giannini and Co.; requests for information should be addressed to the Office of the Chief Signal Officer, Attn: SIGGE, Washington 25, D. C.) has developed a rocket-borne heliograph which gives a photographic record of the missile's altitude relative to the Sun; but this method is confined to daytime use, and requires recovery of films from the missile plus a tedious reduction of data, particularly if vertical coordinates instead of Sun coordinates are needed. In addition the weight of the installation is considerable.

The Air Forces have sponsored the development of a technique using cameras in the rocket to photograph the Earth. (The work was done at Ohio State University. Requests for information should be addressed to Chief of Staff, U. S. Air Force, Deputy Chief of Staff for Materiel, Director of

Research and Development, Attn: AFMR8-4, Washington 25, D. C.) Analysis of the films subsequently to the flight gives missile aspect, but this analysis also is elaborate. Moreover, the method, like the Signal Corps' depends upon the recovery of film, and is confined to daytime use.

The Naval Research Laboratory is attempting to solve the problem for the V-2's with gyroscopes. This method may be used at night as well as during the day, the reduction of data is simple, and the information may be either telemetered or recorded on a rocket-borne film. On the other hand, both the high acceleration of the rocket during powered flight, and its rolling and precessing afterward tend to cause the aspect gyros to tumble. Even if the gyros do not actually tumble, they precess an unknown amount, which introduces errors into the aspect data. The elimination of these errors is the principal problem at present.

A number of the experimenting groups have used photocells to obtain aspect relative to the Sun. In this case the reduction of data is simple. The method, however, is not highly accurate without an excessively elaborate installation; and, furthermore, does not completely determine the missile orientation in space. Also it is again a daytime method.

The Navy Viking, recently tested, stabilizes during free fall by means of air jets. This is perhaps the ideal solution.

Another major problem is that of the very high speeds attained by sounding rockets. The effect of supersonic speeds upon pressure and ion density measurements, for example, is not yet completely known, particularly if the rocket rolls and precesses. Considerable work, both experimental and theoretical, remains to be done in this field.

Finally, the great mass of a rocket like the V-2 has an appreciable effect on cosmic ray experiments performed, and may even mask some important facts. The Aerobee should be considerably better in this respect. The final solution of the problem may well rest with the perfecting of techniques for recovering equipment ejected from the rocket during flight.

The recovery of data--Initially it was supposed that recovery of data from a high altitude rocket would have to depend principally upon radio means. Very soon, however, it was found that destroying the rocket's streamlining by detonation of appropriately placed explosives, caused large portions of the missile to return to Earth at slow enough rates to permit recovery of equipment and film records. It is now customary to sever the V-2 warhead, or warhead plus control compartment, by using TNT, in which case installations in the mid- and tail-sections are almost always recovered. For the Aerobee, the Applied Physics Laboratory suggested severing the tail skirt with primacord, thereby rendering the missile aerodynamically unstable. When this procedure is successful the missile is often retrieved in excellent condition as far as recovery of equipment is concerned.

The impacts of the V-2's are usually very quickly located from optical and radar tracking data, and by air search. The Aerobees, on the other hand, are not as a rule tracked beyond the end of burning either by radar or by optical means. As a consequence the early rockets were not retrieved. Upon the suggestion of the Naval Research Laboratory, however, a system of sound ranging on the rockets, similar to that used in World War I for locating large gun emplacements, was introduced. Since then, all but one of the Aerobees fired at White Sands have been recovered. The sound ranging together with tail skirt blowoff, appear to be an acceptable solution to the problem of recovery of equipment and records from the Aerobee.

Recently the Naval Research Laboratory put an impact computer into operation at White Sands. This instrument takes optical tracking data from two stations separated by about eight miles, and from those data computes for each instant where the missile would land if the rest of its flight were entirely free fall. The predicted impact point is then displayed on a plotting board over a plot of the firing range. In this way, the computer contributes both to range safety and equipment recovery.

In addition to recorders, requiring recovery of the missile, radio telemetering is employed in the sounding rockets. In the V-2's a time modulated pulse system, developed by the Naval Research Laboratory [HEEREN and others, 1946, 1947; NAVAL RESEARCH LABORATORY, 1946ab, 1947ab], is used. Its accuracy is on the order of one per cent.

The Aerobee flights are telemetered by means of a small, 20-pound, FM-on-FM, 6-channel, 85-mc unit developed by the Applied Physics Laboratory [MELTON, 1948]. The overall accuracy of this system is better than five per cent.

At the present time, major reliance is placed on telemetering and the recovery of airborne

recorders from the missile wreckage itself for obtaining data. In the past, attempts have been made to eject equipment from the missile during flight, slowing its downward plunge by some sort of drag device. These attempts have not been too successful, even though, in some cases, it appeared that the ejection occurred as planned. The ejected equipment was not found. Thus the problem is twofold. In addition to lowering the equipment safely to Earth, some reliable means must be devised to locate the impact point. A considerable amount of work is still being expended on these problems, especially by the Air Forces.

Pressures and temperatures in the upper atmosphere--R. J. Havens and his colleagues at the Naval Research Laboratory measured pressures in the atmosphere above White Sands on October 10, 1946 [BEST and others, 1946; NAVAL RESEARCH LABORATORY, 1946b], March 7, 1947 [BEST and others, 1947; NAVAL RESEARCH LABORATORY, 1947b], January 22, 1948 [NAVAL RESEARCH LABORATORY, 1948], and August 5, 1948. The first three sets of measurements were made from V-2's; the last from an Aerobee. The reduced data from the first three dates are presented in Figure 1 together with an average curve showing the relation of ambient pressure to altitude. The August data will be published in the near future.

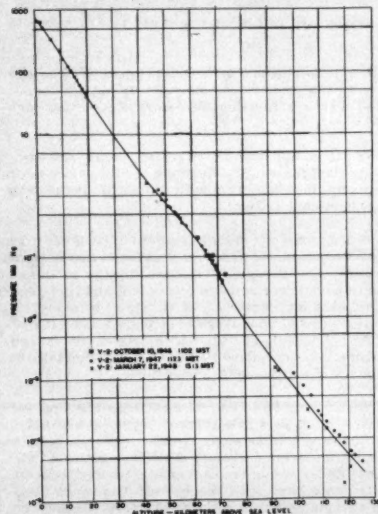


Fig. 1--Relation of ambient pressure to altitude above White Sands, New Mexico

pressures in the neighborhood of 65 km. No yaw was apparent at this altitude. A single gage gave pressures above 90 km. The gage was located on a 15° cone, for which no corrections were made in reducing the data. If corrections for cone angle had been made, assuming no angle of attack, the Taylor-Maccoll theory would have reduced the pressure readings by about 50 per cent. Yaw was present, so that it is fairly safe to assume that at least one point on the measured curve gave ambient pressure. The measurements below 70 km were correct to within ten per cent.

On the flight of January 22, 1948, for each range at least two gages, spaced 180° apart on the rocket, were used. Yaw was not significant below 70 km. Above 70 km the two Philips gages mounted 180° apart at the base of the warhead where the cone angle was about 13°, showed periodic pressure changes varying directly with the roll period of the rocket. It was estimated that ambient pressures were given to within a factor of two when both gages measured the same pressure. Measurements below 70 km were correct to within ten per cent.

Pressures greater than ten mm Hg were measured with bellows gages; those between 10 and 10⁻² mm Hg, with Pirani gages; and those from 10⁻³ to 10⁻⁵ mm Hg, with Philips gages [HAVENS, 1948]. The bellows gages were calibrated with manometers, and the Pirani and Philips gages were referred directly or indirectly to MacLeod gages.

Measurements of pressure were made on a circumference of the rocket just forward of the tail fins. Wind tunnel studies showed that in this region ambient pressures should exist over a wide range of Mach numbers. This was established on several occasions for Mach numbers up to four by comparison of rocket and balloon measurements made within a few hours of each other. Pressure was also measured at various points on the nose section.

The data of October 10, 1946 were obtained with only one gage, the time lag for which was about 1.5 seconds. The data in Figure 1 are not corrected for this time lag. Because only one gage was used, it is not known whether the readings were affected by pitch and yaw of the rocket. The data are accordingly considered to be in the nature of preliminary measurements.

The data taken on March 7, 1947 are also not corrected for time lag of the gages, but in this case all time lags were less than 0.2 second. One gage was used for altitudes near 50 km.

Two pairs of gages spaced 180° apart measured

The differences in the various sets of data for altitudes below 30 km are real and mostly due to seasonal effects. At higher altitudes, particularly above 70 km, these differences are only slightly greater than estimated probable errors in the altitude and pressure measurements. In fact, due to yawing of the rockets, the pressure readings above 90 km can be expected to give no more than a rough indication, within a factor of two or so, of ambient pressures.

An average temperature curve of the atmosphere, based on the March 7, 1947, January 22, 1948, and August 5, 1948 data, is shown in Figure 2. It was calculated from the slope of an average pressure curve on the assumption that sea level composition existed at all altitudes.

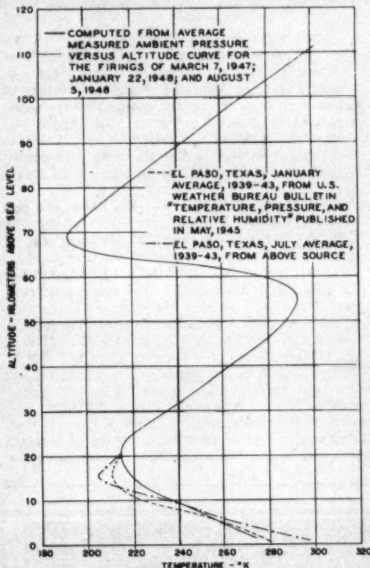


Fig. 2--Relation of temperature to altitude above White Sands, New Mexico

made of carefully polished lithium fluoride which is the most transparent substance known for ultra-violet light. The grating, ruled at the Johns Hopkins University, was four cm long by three cm high and consisted of 15000 lines to the inch on an aluminized spherical surface of 40 cm radius of curvature. Eastman 35 mm 103-0 ultraviolet sensitized film recorded the spectra.

The use of a two-bead system considerably reduced the amount of wasted time due to rolling of the rocket after fuel burnout. To avoid smearing of the spectrograms, the light from one bead was directed to one edge of the film, and that from the other was directed to the other edge.

For the flight of March 7, 1947, the plane path-folding mirror shown in the drawing of Figure 3 was replaced by a cylindrical mirror [JOHNSON and TOUSEY, 1947]. This eliminated astigmatism at one wavelength and greatly reduced it at others. On the other hand, densitometry of the March 7, 1947 spectra was virtually impossible because of the variation in height of the lines which the cylinder produced.

The strongest of the solar spectra obtained so far extended into the ultraviolet to 2100Å. Some

Solar spectroscopy--Because of absorption in the atmosphere, the solar ultra-violet radiation which reaches the Earth's surface is limited to wavelengths above the 2869Å photographed by Götz. The V-2 and Aerobee, however, penetrate to regions in which the sunlight has experienced very little absorption. For this reason R. Tousey, E. Durand and others at the Naval Research Laboratory have sent a number of spectrographs aloft at White Sands, and on four separate flights solar spectra were obtained by this means [NAVAL RESEARCH LABORATORY, 1946b, 1947ab, 1948; BAUM and others, 1946; STRAIN, 1947; DURAND and others, 1947, 1949].

The principal objects of attention so far have been: (1) the Fraunhofer lines in the solar ultra-violet from 2100 to 2900Å; (2) the relative spectral intensity distribution in solar radiation below 2900Å; (3) the vertical distribution of ozone in the Earth's atmosphere; and (4) the solar spectrum in the extreme ultraviolet from 500 to 2000Å.

A schematic drawing of the NRL spectrograph is shown in Figure 3 [NAVAL RESEARCH LABORATORY, 1946a; TOUSEY and others, 1947; JOHNSON and TOUSEY, 1947]. The diagram is to a large extent self-explanatory. As shown, the illuminators were small beads. The purpose in using bead illuminators was to obtain a wide-angle system to eliminate the need for tracking the Sun. Each bead was capable of directing the Sun's light into the spectrograph even when the Sun lay as much as 70° off the principal axis of the system. Also, tests showed that such a bead system required much shorter exposure times than did a conventional slit with a diffuser plate. The beads were two mm in diameter and were

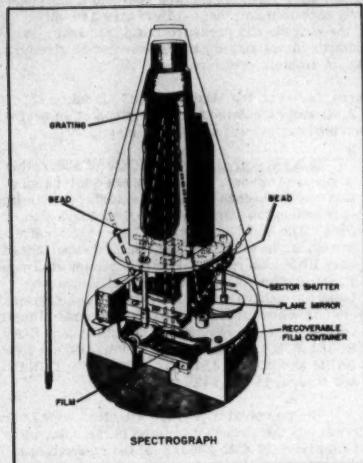


Fig. 3--Schematic drawing of NRL spectrograph

of the spectra are shown in Figure 4 [NAVAL RESEARCH LABORATORY, 1946b, 1947b, 1948; BAUM and others, 1946; STRAIN, 1947; DURAND and others, 1947, 1949]. Shorter wavelengths have not been recorded presumably because of low intensities and instability of the rocket. Attention is now being devoted to stabilization of both the rocket and the spectrograph. If the efforts succeed, it should be possible to record down to 1100A with the presently used instrument.

One of the spectra obtained on March 7, 1947 showed a resolution of 1.5A. This was the best obtained by the Naval Research Laboratory. In a later flight the Applied Physics Laboratory obtained a number of spectra down to 2300A with a resolution of one A or better. The Applied Physics Laboratory spectrograph used a slit and had a dispersion of 34 A per mm as compared with the Naval Research Laboratory's 44 A per mm.

Analyses of the NRL spectra have been published in the following reports; NAVAL RESEARCH LABORATORY [1948], and DURAND and others [1947, 1949]. The APL spectra were reported by HOPFIELD and CLEARMAN [1948]. Approximately 150 new Fraunhofer lines in the solar spectrum were observed. Most of these were blends of two or more closely spaced lines. Absorption by Si I at 2882 A, Mg I at 2852 A, and Mg II at 2800 A are clearly seen in the trace of Figure 5. Of

greatest interest perhaps is the Mg II doublet at 2796 and 2803 A corresponding to the H and K lines of calcium. The two absorption lines were not resolved but appeared as a great region of absorption extending over at least 50 A, and possible as much as 200 A. At exactly 2796 and 2803 A, however, prominent narrow emission lines appeared, much as is observed in the H and K lines in the flash spectrum of the Sun. The presence of these lines was predicted by Menzel. They undoubtedly originate in the high temperature, low pressure region high in the Sun's atmosphere and above the reversing layer.

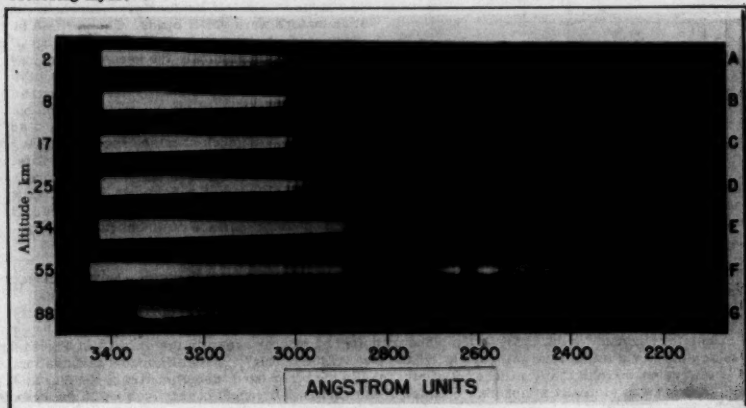


Fig. 4--A series of solar spectra taken from a V-2 rocket, October 10, 1946, White Sands, New Mexico

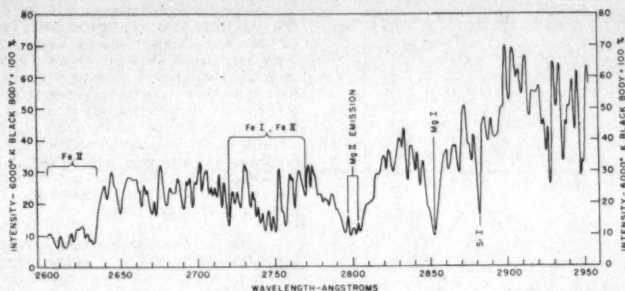


Fig. 5--NRL V-2 solar spectrum no. 43 made on March 7, 1947, plotted on a linear intensity scale relative to intensity of a black body at 6000° K

Characteristic of the spectrum was a number of great dips in intensity. Most of these were found to be caused by Fe I and Fe II multiplets. Depressions from 2204-2221 Å, from 2255-2279 Å, and from 2440-2470 Å, however, could not be explained in terms of known intensities of strong absorption lines. A possible explanation lies in band absorption by constituents of the Earth's or the Sun's atmosphere. It may be noted that there does exist a strong band of nitric oxide centered at 2264 Å.

The relative spectral intensity in the solar ultraviolet was measured by photographic photometry. Figure 5 shows the solar energy distribution plotted as a function of wavelength from the March 7, 1947 spectra. The intensities are plotted as percentages of the intensity values for a 6000° K black body. The black-body curve was adjusted so that its maximum coincided with that of the solar intensity curve at about 4800 Å. It is seen that the solar intensity curve lies well below the 6000° K black body curve. It is difficult to say exactly what this means. Probably the absorption lines are so many and so closely spaced in the ultraviolet that much of the radiation in this region actually comes from a portion of the Sun's atmosphere both higher and cooler than the source of the visible solar light.

From the series of spectra obtained at various altitudes on October 10, 1946, the vertical distribution of ozone was determined by means of photographic photometry. Preliminary results were presented in an NRL report [NAVAL RESEARCH LABORATORY, 1947]. Tousey reports, however, that an improved analysis of the data has just been completed. The more recent analysis shows that the lower altitude maximum reported earlier probably did not exist. Tousey states also that the total ozone content was around two mm, somewhat lower than the figure initially given.

Values of ozone concentration for the top edge of the ozone layers were measured for the first time and are in rather good agreement with the values calculated on a photochemical basis by Wulf and Deming. No ozone was observed above 48 km, placing the concentration above this altitude below the detectable limit of 0.0005 cm/km. Wulf and Deming predicted less than 0.00005 cm/km for this region.

The October 10 spectrogram taken at 34 km showed an appreciable blackening in the neighborhood of 2200 Å. This can be seen in the densitometer trace of Figure 6 in which the wavelength scale is compressed to emphasize the hump in the trace. Ozone absorption is small in this region, and severe molecular oxygen absorption occurs at shorter wavelengths. Thus there exists here a rather poor "window," as was pointed out by Meyer.

Cosmic radiation at high altitudes--A number of cosmic ray experiments have been performed in White Sands rocket flights by G. J. Perlow, E. H. Krause and others. The principal aim of the Naval Research Laboratory so far has been to provide answers to questions which, because of the atmosphere, cannot be answered satisfactorily on the basis of lower altitude experiments. A paper giving a detailed account of the results to date is now in preparation. Some of the more important conclusions are presented here.

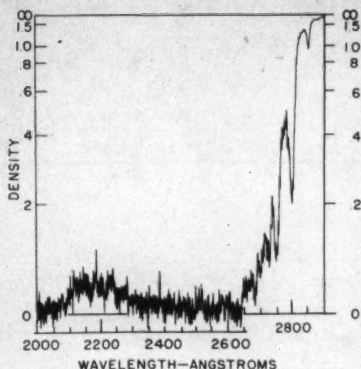


Fig. 6--NRL V-2 solar spectrum no. 23 taken at 35 km on October 10, 1946; compressed wavelength scale used to emphasize the "hump" near 2200 A

exhibited by the radiation other than the Wheeler electrons described above according to the report of Perlow to Physical Society in May, 1947.

A six-inch cloud chamber was sent aloft to 159 km on January 22, 1948 [NAVAL RESEARCH LABORATORY, 1948; GOLIAN and others, 1949]. A number of photographs were obtained. One heavy track observed was of greatest interest. On the basis of penetration, ionization, and scattering characteristics, one concludes that the track was caused by a heavy primary, quite probably of greater charge and mass than a proton.

The Applied Physics Laboratory is also carrying on an extensive cosmic ray program. In a series of V-2 and Aerobee flights, single counter measurements have shown that the average counting rate of a geiger counter above the atmosphere at White Sands, geomagnetic latitude 41° N corresponds to an average unidirectional intensity of 0.12 counts/cm² sec steradian [VAN ALLEN and TATEL, 1948ab; VAN ALLEN, 1948; GANGNES and others, 1949]. From measurements of the anisotropy of the total high altitude radiation APL derives 0.08 counts/cm² sec steradian as an upper limit to the intensity of primary radiation. It is of interest to note that APL also has shown, on the basis of a measured transition curve for the primaries in lead, that electrons cannot be an important part of the primary cosmic radiation [VAN ALLEN and others, 1949]. Studies of burst rates in an ionization chamber have revealed essentially a linear increase with altitude, corresponding to an absorption coefficient of approximately $1/200$ (gm/cm²)⁻¹ until the free space rate is attained [VAN ALLEN and TATEL, 1948a].

The Ionosphere--A number of experiments to determine the density and nature of the ionization in the D, E and F layers of the ionosphere are being performed in rockets by the Naval Research Laboratory. At the present time data are available from one of these, a phase beat experiment devised by J. C. Seddon, involving the propagation of radio waves from the rocket during flight [NAVAL RESEARCH LABORATORY, 1946a, 1947b].

The experiment detailed descriptions of which have been given in the references indicated, furnishes estimates of effective electron densities rather than actual ion densities. From the data of March 7, 1947, a day of worldwide radiofade-out, this effective electron density was found to be less than 10^4 per cm³ below 83 km. The density increased to about 2.3×10^5 per cm³ at 111 km. Preliminary analysis of data acquired on January 22, 1948 shows an effective electron density of less than 10^4 per cm³ below 85 km, increasing to about 2.3×10^5 per cm³ at 100 km. The density was appreciably less than 10^5 at 130 km, and appears to have increased again at 155 km.

A counter experiment on June 28, 1946 [NAVAL RESEARCH LABORATORY, 1946a; GOLIAN and others, 1946a] showed unexpectedly large numbers of showers produced in the rocket structure. A large percentage of the rays above the atmosphere were highly penetrating. Counter experiments in other rockets measured absorption of the upper air-radiation in 2, 4, 12, and 14 cm of lead. The shower production under each thickness was also determined [NAVAL RESEARCH LABORATORY, 1946b, 1947ab, 1948; GOLIAN and others, 1946b; GOLIAN and KRAUSE, 1947; PERLOW and SHIPMAN, 1947].

Analysis of the experimental data showed that there is a large flux of easily absorbed particles in the upper atmosphere, the intensity of which appears to increase with increasing zenith angle. Presumably this component is non primary. Wheeler suggests that these are electrons from meson decay which are trapped in the Earth's magnetic field. The ones observed at White Sands probably originated above South America and spiraled about the field lines to reach the point of observation.

The data also show that not more than nine per cent of the total radiation can be primary electrons. This can be deduced from the penetration and shower production characteristics

described above according to the report

Further analysis of the data available is underway. Results will be published in the near future. Additional experiments of this type will be performed in V-2's and Vikings. Also, effort will be devoted to determining the precise nature of the ionization in the ionosphere.

High altitude photography--Early in the rocket program the Applied Physics Laboratory secured the first photographs of the Earth taken from a high altitude rocket. The highest of these was taken at 60 mi. Later, on March 7, 1947, the Naval Research Laboratory obtained the first photographs taken above 100 mi [BERGSTRAHL, 1947]. Since then both APL and NRL have secured additional high altitude photographs. APL, especially, has turned out a remarkable series of such pictures. To the meteorologist these photographs are of value in the study of widespread meteorological conditions. The available records have been turned over to the Weather Bureau for analysis.

The overall upper atmosphere rocket program--Most of the work described above was done by the Naval Research Laboratory. In its general aspects the NRL program is similar to those of the Applied Physics Laboratory, the Army Signal Corps, and the Air Forces. Each working agency has a member on the Upper Atmosphere Rocket Research Panel, which informally correlates and co-ordinates the various activities. The Panel has no official status or charter, and all coordination is actually effected by the scientists' natural distaste for doing something that is being or already has been done adequately. The success of this method is amply attested to by the lack of any wasteful duplication of effort in the program so far.

The Applied Physics Laboratory has measured the total magnetic field above the Earth to 115 km altitude. No anomalies exceeding one milligauss were found in the D and E layers over White Sands (private communication to the author by J. A. Van Allen). APL also established the feasibility of using smoke puffs to determine winds between 100,000 and 200,000 ft.

The Signal Corps has since then measured such winds using specially generated smoke clouds. The reduced data are not yet available. The Signal Corps has also made rough measurements of temperatures to 50 or 60 km by measuring the velocity of sound generated by explosive charges fired from the rocket on ascent. Samples of the atmosphere near 50 mi above the Earth have been taken and are presently being analyzed. The search is for helium. Knowledge of the helium content should give some information about the relative importances of mixing and settling processes in the upper atmosphere.

Conclusion--The fair amount of success enjoyed thus far in the rocket upper atmosphere program is gratifying. Nevertheless, the past years must be regarded as a beginning phase. The ultimate potentialities of the rocket, and perhaps some day the satellite vehicle, are yet to be realized.

Acknowledgments--The author desires to express his thanks to many of his colleagues at the Naval Research Laboratory for helpful discussions on the material presented above, particularly to R. J. Havens (pressures and temperatures), R. Tousey (spectroscopy), G. J. Perlow (cosmic rays), and J. C. Seddon (ionosphere). The author is also grateful to J. A. Van Allen for providing a digest of the Applied Physics Laboratory's results, and to M. J. Ference for a similar digest of the Signal Corps' work.

References

- BAUM, W. A. and Others, Solar ultraviolet spectrum to 88 kilometers, *Phys. Rev.* v. 70, pp. 781-782, 1946.
BERGSTRAHL, T. A., Photography from the V-2 at altitudes ranging up to 160 kilometers, *Naval Res. Lab. Rep. R-3083*, 1947.
BEST, N. R. and Others, Pressure and temperature measurements in the upper atmosphere, *Phys. Rev.*, v. 70, p. 985, 1946.
BEST, N. R. and Others, Pressure and temperature of the atmosphere to 120 km, *Phys. Rev.*, v. 71, pp. 915-916, 1947.
DURAND, E., Rocket-sonde research at the Naval Research Laboratory, part of a chapter in *The atmospheres of the Earth and the planets*, University of Chicago Press, 1949.
DURAND, E. and Others, Solar absorption lines between 2950 and 2200 Angstroms, *Phys. Rev.*, v. 71, p. 827, 1947.
DURAND, E. and Others, Analysis of the first rocket ultraviolet spectra, *Astrophys. J.*, v. 109, pp. 1-16, 1949.
GANGNES, A. V. and Others, The cosmic ray intensity above the atmosphere, *Phys. Rev.*, v. 75, p. 57, 1949.
GOLIAN, S. E. and KRAUSE, E. H., Further cosmic ray experiments above the atmosphere, *Phys.*

- Rev., v. 71, pp. 918-919, 1947.
- GOLLAN, S. E. and Others, Cosmic radiation above 40 miles, *Phys. Rev.*, v. 70, pp. 223-224, 1946a.
- GOLLAN, S. E. and Others, Additional cosmic ray experimentation in the V-2 rocket, *Phys. Rev.*, v. 70, pp. 776-777, 1946b.
- GOLLAN, S. E. and Others, V-2 cloud chamber observation of a multiply-charged primary cosmic ray, *Phys. Rev.*, v. 75, pp. 524-525, 1949.
- HAVENS, R. J., Temperature and pressure measurements in rockets, Paper 48-1-3, *Inst. Soc. of Amer.*, presented Sep. 13-17, 1948.
- HEEREN, V. L. and Others, Telemetering equipment developed and provided by the Naval Research Laboratory for general use in the V-2 firings, *Naval Res. Lab. Rep. R-3013*, 1946.
- HEEREN, V. L. and Others, Telemetering from V-2 rockets, *Electronics*, v. 20, pp. 124-127, 1947.
- HOPFIELD, JOHN J. and HAROLD E. CLEARMAN, JR., Ultraviolet spectrum of the Sun from V-2 rockets, *Phys. Rev.*, v. 73, pp. 877-884, 1948.
- JOHNSON, F. S. and R. TOUSEY, Reduction of astigmatism in the NRL rocket spectrograph, *J. Opt. Soc. Amer.*, v. 37, p. 991, 1947.
- KRAUSE, E. H., High altitude research with V-2 rockets, *Proc. Amer. Phil. Soc.*, v. 91, pp. 430-446, 1947.
- MELTON, G. H., Multichannel radio telemetering for rockets, *Electronics*, v. 21, pp. 106-109, 1948.
- NAVAL RESEARCH LABORATORY, Upper atmosphere research report 1, Rep. R-2955, 1946a.
- NAVAL RESEARCH LABORATORY, Upper atmosphere research report 2, Rep. R-3030, 1946b.
- NAVAL RESEARCH LABORATORY, Upper atmosphere research report 3, Rep. R-3120, 1947a.
- NAVAL RESEARCH LABORATORY, Upper atmosphere research report 4, Rep. R-3171, 1947b.
- NAVAL RESEARCH LABORATORY, Upper atmosphere research report 5, Rep. R-3358, 1948.
- NEWELL, H. E., JR., Exploration of the upper atmosphere by means of rockets, *Sci. Mon.*, v. 64, pp. 453-463, 1947.
- NEWELL, H. E., JR., Upper atmosphere research with V-2 rockets, *Naval Res. Lab. Rep. R-3294*, 1948.
- PERLOW, G. J. and J. D. SHIPMAN, JR., Non-primary cosmic ray electrons above the Earth's atmosphere, *Phys. Rev.*, v. 71, pp. 325-326, 1947.
- STRAIN, C. V., Solar spectroscopy at high altitudes, *Sky and Telescope*, v. 6, pp. 3-6, 1947.
- TOUSEY, R. and Others, Solar spectrograph for a V-2 rocket, *J. Opt. Soc. Amer.*, v. 37, p. 523, 1947.
- VAN ALLEN, J. A., Exploratory cosmic ray observations at high altitudes by means of rockets, *Sky and Telescope*, v. 7, pp. 171-175, 1948.
- VAN ALLEN, J. A. and H. E. TATEL, Cosmic-ray bursts in the upper atmosphere, *Phys. Rev.*, v. 73, pp. 87-88, 1948a.
- VAN ALLEN, J. A. and H. E. TATEL, Cosmic ray counting rate of a single gieger counter from ground level to 161 kilometers altitude, *Phys. Rev.*, v. 73, pp. 245-251, 1948b.
- VAN ALLEN, J. A. and Others, The Aerobes sounding rocket, a new vehicle for research in the upper atmosphere, *Science*, v. 108, pp. 746-747, 1948c.
- VAN ALLEN, J. A. and Others, Nature of the primary cosmic radiation as revealed by transition effects in lead and within the atmosphere; paper presented at the New York meeting of the Amer. Phys. Soc., January 26-29, 1949.

Naval Research Laboratory,
Office of Naval Research,
Washington, D. C.

(Manuscript received April 19, 1949, and as revised July 20, 1949; presented at the Symposium on the Upper Atmosphere, Twenty-Third Regional Meeting, Los Angeles, California, February 5, 1949; open for formal discussion until July 1, 1950.)

A STATISTICAL MODEL OF INSTANTANEOUS POINT AND DISK SOURCES WITH APPLICATIONS TO OCEANOGRAPHIC OBSERVATIONS

George F. McEwen

(Contributions from the Scripps Institution of Oceanography, New Series, No. 437)

Abstract -- In general, a space distribution of particles within water, or of properties of the water, may be considered as resulting from the movements of small objects from some known or hypothetical initial position. Such displacements are regarded as the resultant of a large number of small positive or negative movements following probability laws. In the one-dimensioned case, the frequency of a resultant displacement x and the standard deviation of the positions of the moving objects are derived from a limiting form of the binomial series. This statistical equation is analogous to the solution of the differential equation of diffusion in one dimension from an initial concentration on a plane perpendicular to the x -axis. The constants in this differential equation of diffusion may be equated to the corresponding parameters of the statistical equation, thus providing a statistical interpretation of the diffusion equation. These results are generalized to the familiar two-dimensioned instantaneous point source problem. Later this is generalized to a disk source. Various applications of these solutions are made to observations of drift bottles in the sea and to temperature, salinity, and plankton concentration in certain stagnant areas of the sea, associated with large horizontal eddies. The diffusion coefficients thus obtained from concentrations changing with time, the dynamic case, agree well with those derived from a steady state corresponding to an assumed equilibrium between advection and diffusion at the boundary between water masses of different properties.

Statistical theory of space distribution of particles -- Probability or chance always enters into the distribution of organisms or other objects in space, and influences all methods of collecting data about such distributions, and interpreting the results [BUCHANAN-WOLLASTON, 1938]. In general, a space distribution of objects or properties may be considered to be due to their movement from some known or hypothetical position, and it is in such movement that the element of chance will be regarded as entering. Chance may influence both the amount and direction of movement, which may be in one, two, or three dimensions.

The principle may be illustrated by considering first the simplest case of pure random movement of objects in one direction only. This movement may be considered as the sum of a great number of small equal movements, each of which is equally likely to be in one direction or in the opposite direction; for example, to the right or to the left. Then the space distribution of N objects after n "chances" of movement will be given by the terms of the expansion of the binomial $N(1/2 + 1/2)^{2n}$.

The frequency, $F_{m,(2n-m)}$ of m movements to the left and $(2n-m)$ movements to the right is given by the $(m+1)$ st term,

$$F_{m,(2n-m)} = N (1/2)^{2n} \left[\frac{2n!}{m! (2n-m)!} \right] \dots \dots \dots (1)$$

where the exponents in this descriptive expression [] equal respectively the number of movements to the left and to the right.

In practical applications of diffusion we are concerned with large values of n , and use a well-known approximation to the term $F_{m,(2n-m)}$ of the binomial expansion,

$$F_{m,(2n-m)} = N (1/2)^{2n} \left[\frac{2n!}{m! (2n-m)!} \right] \sim N e^{-\frac{1}{2} \frac{(n-m)^2}{n}} / \sqrt{\pi n} \dots \dots \dots (2)$$

The approximation is closer the larger the value of n .

Consider the frequency F_x of a resultant of $x/h = (n-m)$ movements to right or to the left. x equals the resultant distance and $x = 0$ corresponds to the origin where there are n movements to the right and m to the left. Substitute in the approximate expression and use the equality sign, since we are concerned with large values of n . The result is

$$F_x = Ne^{-(x^2/nh^2)}/\sqrt{\pi n} \dots \dots \dots (3)$$

which is the frequency of a resultant of x/h movements over an elementary distance h or of a resultant distance x , expressed in terms of h as a unit.

In the binomial series $(1/2 + 1/2)^{2n}$ the mean equals n and the standard deviation equals $\sqrt{n/2} = \sigma$.

$h\sqrt{n/2} = \sigma h$ is defined as the spread of the moving objects, or the standard deviation of the distance through which they have moved.

The whole range of the distribution is given by the number of terms of the binomial; it extends from n units to the left to n units to the right of the center, and including the center space, is $2n + 1$ units in length. The total number of movements, $2n$, is evidently proportional to the time during which the objects are subject to movement.

Therefore, the spread, $h\sqrt{n/2}$, from the center is proportional to the square root of the time and may accordingly be written

$$\text{Spread} = h\sqrt{(n-ct)/2} = \sqrt{kt} = h\sqrt{n/2} = \sigma \dots \dots \dots (4)$$

where c equals number of movements per unit time. The coefficient k depends upon the conditions of movement. Also $\sqrt{k} = h\sqrt{c/2}$ or $k = h^2(c/2) = L^2/T$, $\sqrt{n} = (\sqrt{2}/h)\sqrt{kt}$, and

$$F_x = Nhe^{-(x^2/2kt)}/\sqrt{2\pi kt} \dots \dots \dots (5)$$

where $\sqrt{kt} = \sigma$, the standard deviation of the distance of the particles from the origin.

The integral from $-\infty$ to $+\infty$ of the frequency F_x of the number of particles with respect to the number of movements should equal N , the total number of particles. This result is verified by evaluating the following integral

$$\int_{-\infty}^{\infty} (F_x)h^{-1}dx = (1/h)Nh \int_{-\infty}^{\infty} [e^{-(x^2/2kt)}/\sqrt{2\pi kt}] dx \dots \dots \dots (6)$$

We shall now compare appropriate solutions of the differential equation of diffusion and heat conduction with the above expression for F_x in order to obtain a physical interpretation of the coefficients of diffusion and heat conduction. From laboratory experiments

$$dm = \alpha^2 A (\partial S / \partial x) dt \dots \dots \dots (7)$$

where dm equals the amount of substance that diffuses through the area A in time dt , S equals concentration of the substance or mass per unit volume of the solution, and α^2 equals the coefficient of diffusion.

The following diffusion equation in one dimension may be derived from the above principle,

$$\partial S / \partial t = \alpha^2 \partial^2 S / \partial x^2 \dots \dots \dots (8)$$

where α^2 is the coefficient of the diffusion and has the dimension L^2/T .

To compute the dispersion from an instantaneous source of material we must obtain an appropriate solution of the diffusion equation. The solution

$$S = (1/2\alpha\sqrt{\pi t}) \int_{-\infty}^{\infty} f(\lambda) e^{-(\lambda-x)^2/4\alpha^2 t} d\lambda \dots \dots \dots (9)$$

reduces to $f(x)$ for $t = 0$.

Consider a thin section at distance λ and of thickness $\Delta\lambda$. Material is suddenly distributed through the section so that there are M grams in a volume of unit area and thickness $\Delta\lambda$.

Then at time $t = 0$, S is the concentration or mass per unit volume in this section and equals $M/\Delta\lambda$; $S = 0$ at all other sections. Therefore

$$S = (1/2\alpha\sqrt{\pi t}) \int_{\lambda}^{\lambda+\Delta\lambda} (M/\Delta\lambda) e^{-(\lambda-x)^2/4\alpha^2 t} d\lambda \dots \dots \dots (10)$$

$$\lambda < \lambda' < \lambda + \Delta\lambda$$

$$S = (1/2\alpha\sqrt{\pi t}) (M/\Delta\lambda)e^{-(\lambda' - x)^2/4\alpha^2 t} \Delta\lambda \dots (11)$$

As $\Delta\lambda$ approaches zero, this reduces to

$$S = Me^{-(x^2/4\alpha^2 t)}/2\alpha\sqrt{\pi t} \dots (12)$$

if the origin is at $\lambda = \lambda' = 0$. The integral of this value of S from $-\infty$ to $+\infty$ should equal the total amount of material M , as the following computation shows

$$\int_{-\infty}^{\infty} S dx = (M/\sqrt{\pi}) \int_{-\infty}^{\infty} e^{-(x^2/4\alpha^2 t)} d(x/2\alpha\sqrt{t}) = M \left\{ (1/\sqrt{\pi}) \int_{-\infty}^{\infty} e^{-B^2} dB \right\} = M \dots (13)$$

Similarly for an instantaneous heat source the differential equation is

$$\partial\theta/\partial t = a^2 \partial^2\theta/\partial x^2 \dots (14)$$

where the thermometric conductivity is a^2 . The solution is

$$\theta = Qe^{-(x^2/4a^2 t)}/2a\sqrt{\pi t} \dots (15)$$

where

Q = strength of the source = $q/\rho c$,
 q = units of heat per unit area suddenly generated at the source, $x = 0$,
 ρ = density of the material,
 c = specific heat,
 $1/\rho c$ = rise in temperature caused by one unit of heat.

The correctness of each of these solutions, S and θ , can be shown by substitution in the differential equation.

On comparing (5) the expression of frequency

$$F_x = Nhe^{-(x^2/2kt)}/\sqrt{2\pi kt} \dots (16)$$

and the solution of (12) the differential equation of diffusion

$$S = Me^{-(x^2/4\alpha^2 t)}/\sqrt{4\pi\alpha^2 t} \dots (17)$$

it is evident that $4\alpha^2 = 2k$ or $\alpha^2 = k/2 = ch^2/4$. But the standard deviation of the dispersed particles is $\sigma = \sqrt{kt} = \sqrt{2\alpha^2 t}$. Therefore α^2 , the coefficient of diffusion, equals $\sigma^2/2t$, and has the dimension L^2T^{-1} .

The expression of frequency (5) divided by N is the a probability P_x , and, to consider motion in two dimensions, multiply the two corresponding equations and obtain

$$P_{xy} = [h_1 e^{-(x^2/2k_1 t)}/\sqrt{2\pi k_1 t}] [h_2 e^{-(y^2/2k_2 t)}/\sqrt{2\pi k_2 t}] \\ = (h_1 h_2 / 2\pi \sqrt{k_1 k_2}) [e^{-(x^2/2k_1 t) - (y^2/2k_2 t)}] / t \dots (18)$$

which may be compared with the solution of the differential equation of diffusion from a point source for two dimensions

$$S = (M/2\pi\sqrt{4\alpha_1^2\alpha_2^2}) [e^{-(x^2/4\alpha_1^2 t) - (y^2/4\alpha_2^2 t)}] / t \dots (19)$$

Evidently $\alpha_1^2 = k_1/2$, $\alpha_2^2 = k_2/2$, and the standard deviation in the x and y directions are respectively

$$\sigma_x = \sqrt{2\alpha_1^2 t} \text{ and } \sigma_y = \sqrt{2\alpha_2^2 t} \dots (20)$$

Assuming circular symmetry and a constant coefficient of diffusion α^2 , the foregoing equation for S reduces to the familiar point source solution

$$S = Me^{-(r^2/4\alpha^2 t)}/4\pi\alpha^2 t = S_1 r_1^2 e^{-(r^2/4\alpha^2 t)}/4\alpha^2 t \dots (21)$$

where $r = \sqrt{x^2 + y^2}$ = distance from the center, S_1 = initial concentration.

Using the following definition of the standard deviation in the two-dimensional case

$$\sigma = \sqrt{\int_0^\infty S(2\pi r) r^2 dr / \int_0^\infty S(2\pi r) dr} \quad (22)$$

and substituting for S the foregoing point source solution, with A in place of α^2 , the same value is found for the standard deviation as before, namely

$$\sigma = \sqrt{2At} \quad (23)$$

Because of irregularities and lack of symmetry of the observed distribution it may be advantageous to use the proportion of material outside of a circle of radius r to the total amount

$$P = 1 - \int_r^\infty S(2\pi r) dr / M = 1 - e^{-(r^2/4At)} \quad (24)$$

assuming a point source.

Another formula for computing A can be derived by assuming the theoretical distribution of the material at a given instant of time to approximate closely enough to the observed distribution, if a suitable value, T_0 , is substituted for the time t . T_0 equals the time from the initial condition, $t = 0$, to the given instant. Let T_1 equal the time measured from the same origin to a later instant. Determine from a chart of observed distributions at any time the distance from the center of dispersal beyond which no concentration can be detected. This distance would be $r = \lambda$, where according to probability theory $\lambda \sim 2.5$, and from the statistical theory $\sqrt{2AT_0} = \sigma_0 = r_0/\lambda$, $\sqrt{2AT_1} = \sigma_1 = r_1/\lambda$.

From (5) and (6) the coefficient of eddy diffusion can be computed in either of two ways,

$$A = (\sigma_1^2 - \sigma_0^2)/2(T_1 - T_0) = (r_1^2 - r_0^2)/2\lambda^2(T_1 - T_0) \quad (25)$$

The second expression, not involving σ , is adapted to rapid approximate estimates depending upon judgment of the distances r_0 and r_1 , beyond which there is no concentration.

Equation (25) also applies to the one-dimension case, the initial concentration being along the surface, if the variable distance x , perpendicular to the surface, is substituted for r .

Application of the foregoing theory to drift bottles--Observations on drift bottles [TIBBY, 1939] serve to illustrate the application of (24). Tibby lists the proportion of drift bottles released at each of a number of stations in the Pacific off Southern California. Since recoveries were made only along the shore, it was assumed that the proportion that would be recovered outside of a circle of radius equal to the distance from the station to the shore could be determined by multiplying the listed proportion recovered by a factor equal to the circumference of the circle, divided by the distance along the shore where recoveries were made. Although the uncertainties due to field conditions preclude accurate results the theory was applied, and the results, presented in Table 1, appear to give values of the coefficient of lateral eddy diffusion in general agreement with those found in the same region from applications of different formulae to data on temperature and salinity.

Generalization of problem of diffusion from point source to disk source--It is recognized that the point source formula is of limited application to conditions in the sea. The assumptions involve a very small initial area, or great distance from the center or great value of the time. Accordingly, it is necessary to generalize the point source formula to permit an initial concentration over a circular area of any size, and valid for any values of the time and distance. This problem may be solved by a method which will now be outlined [McEWEN, 1946].

Integration from 0 to ∞ with respect to λ , of the elementary solution,

$$S = F(\lambda)e^{-\lambda^2 At} J_0(\lambda r)$$

of the differential equation of diffusion

$$\partial S / \partial t = A[(\partial^2 S / \partial r^2) + (1/r)(\partial S / \partial r)] \quad (26)$$

results in a solution subject to the boundary conditions, $S(0, r) = S_1$ for $r < r_1$ and $S(0, r) = 0$ for $r > r_1$, where r_1 is the radius of the circle of initial concentration S_1 , if the arbitrary function $F(\lambda)$ is properly chosen. The resulting formal solution is

$$S = S_1 r_1 \int_0^\infty J_1(\lambda r_1) J_0(\lambda r) e^{-\lambda^2 At} d\lambda \quad (27)$$

where J_0 and J_1 are Bessel Functions of the first kind and $F(\lambda)$ was determined from the following integral of Weber,

$$\int_0^{\infty} J_1(x) J_0(\alpha x) dx = \begin{cases} 1, & \alpha^2 < 1; \\ 1/2, & \alpha^2 = 1; \\ 0, & \alpha^2 > 1 \end{cases} \dots \dots \dots (28)$$

The formal solution reduces to

$$S = S_1 [1 - e^{-(r_1^2/4At)}] \dots \dots \dots (29)$$

and

$$S = (S_1/2) [1 - e^{-(r_1^2/2At)} I_0(r_1^2/2At)] \dots \dots \dots (30)$$

respectively for $r = 0$, and $r = r_1$, where I_1 is the modified Bessel Function of the first kind.

To transform the general solution into one convenient for interpretation and numerical work, differentiate it with respect to r and add the integral of this result with respect to r from 0 to r to the value corresponding to $r = 0$, thus obtaining

$$S = S_1 [1 - e^{-(r_1^2/4At)}] - S_1 r_1/2At e^{-(r_1^2/4At)} \int_0^r e^{-(r^2/4At)} I_1(rr_1/2At) dr \dots \dots (31)$$

Repeated integration by parts in twoways, and application of Sonine's expansion

$$[e^x + I_0(x)]/2 = I_0(x) + I_1(x) + I_2(x) + \dots,$$

results in the following solutions

$$S = S_1 \left\{ 1 - e^{-(r - r_1)^2/4At} [I_0(rr_1/2At) + (r/r_1) I_1(rr_1/2At) + (r/r_1)^2 I_2(rr_1/2At) + \dots] \right\} \text{ for } r < r_1, \dots \dots \dots (32)$$

and

$$S = S_1 e^{-(r - r_1)^2/4At} [(r_1/r) I_1(rr_1/2At) + (r/r_1)^2 I_2(rr_1/2At) + \dots] \text{ for } r > r_1 \dots (33)$$

where $e^{-x} I_1(x)$ is denoted by $f_1(x)$, which varies between the limits 0 and 1 and decreases as i increases. Both expressions reduce to the particular solution already obtained, if r_1 is substituted for r . Also each series converges more rapidly than the geometrical series resulting from substituting 1 for $f_1(x)$, since these functions decrease as i increases.

The effect of size r_1 of the initial circle of concentration on the distribution of a given mass M of material can be determined as follows: Let S correspond to an initial concentration in a circle of radius r_1 , and to a given total amount of material M . Denote by S' the concentration corresponding to the same value of M but for $r_1 \rightarrow 0$, the point source problem. Then by substituting approximations to $f_i(x)$, assuming x to be small, in the exact equation, the following approximate relation can be derived, assuming $(rr_1/2At)$ and $(r_1^2/4At)$ to be small < 1 , and $r > r_1$

$$S \sim [1 - rr_1/2At + (7/12)(r_1^2/4At) - (r_1^2/4At)(rr_1/2At) + (11/24)(rr_1/2At)^2 + \dots] S' \dots \dots \dots (34)$$

This approximate equation can be used only if the time is sufficiently great in relation to the product of the distances rr_1 . It is based upon the following approximations

$$\begin{aligned} f_0(x) &\sim 1 - x + (3/4)x^2 - (5/12)x^3 \\ f_1(x) &\sim (1/2)x(1 - x) + (11/48)x^3 \dots \dots \dots (35) \\ f_2(x) &\sim (1/6)x(1 - x^2/24)I_1(x) \end{aligned}$$

corresponding to small values of $x < 1$.

Table 1--Estimates of A

Station	Proportion recovered	Factor to give proportion for complete circle	Factor times proportion ^a	$\alpha = r^2/4At$
12	0.25	2.0	0.50	0.6931
57	0.43	1.0	0.43	0.844
74	0.06	3.0	0.18	1.715
75	0.08	3.0	0.24	1.427
76	0.17	3.0	0.51	0.673
77	0.014	3.0	0.042	3.17
Median values of sta. 74-77	0.07	3.0	0.21	1.651
All stations, 5943 bottles	0.032	3.0	0.10	2.3026

^a Factor times proportion equals observed $e^{-\alpha}$

Assuming $r_1/2A = 1$ (see Table 2)

$$S \sim [1 - r/t + (7/12)(r_1/2t) - (r_1/2t)(r/t) + (11/24)(r/t)^2 - \dots] S' \dots \dots \dots (36)$$

Therefore, if r or $r_1 = 1$ kilometer, only values of $t > 1$ day could be used. This equation serves to determine whether for given conditions the point source solution could be used as a sufficiently close approximation, and affords a method of correcting this solution.

Application of instantaneous disk source theory--Studies of large horizontal eddies in the ocean off Southern California [McEWEN, 1948] involved the diffusion of vorticity from an initial concentration in large circular areas, according to (32) and (33), and implies the presence of cold stagnant areas of high salinity, roughly circular, of radii from ten to 80 km. From charts of the distribution of surface temperature and salinity at intervals of about two weeks, the relation of temperature to distance, from the center, and of salinity was determined. From charts prepared later the relation of diatom concentration to distance from the center was also determined. Equation (37) was fitted to the relation to distance from the center at the earliest time in each case, and substitution of the successive times of observation in the corresponding formula provided expected values for comparison with these observations. For convenience a scale transformation of the temperature and concentration was made such that the equation for temperature reduced to $A(S - S_0) = 1 - []$, and the equation for concentration reduced to $B(S - S_0) = 1 + []$, where $[]$ = coefficient of S_1 in (32) and (33), or the equivalent

$$\left\{ 1 - e^{-c} - 2c \int_0^\theta e^{-c(1-\theta)^2} f_1(2c\theta) d\theta \right\} \dots \dots \dots (37)$$

in which $c = r_1^2/4At$, $\theta = r/r_1$, $2c\theta = rr_1/2At$.

In general, the results shown in Figures 1 to 5 indicate a rough agreement between theory and observation. Furthermore, the coefficients of eddy diffusion thus found, and presented in Table 2, are in good agreement with those determined from drift bottles, and from applications of equilibrium formulae to the same region [SVERDRUP and FLEMING, 1941]. From the equation $\partial(A_y \partial S / \partial y) / \partial y = \partial(uS) / \partial x$, where y denotes the distance perpendicular to the coast and x , the distance parallel to the coast, they found that A_y varied from $(0.1$ to $5) \times 10^6$, and averaged 2.2×10^6 . Applying the mixing equation $A \partial^2 S / \partial y^2 = u \partial S / \partial x$ to the salinity distribution, they found that $A = (5$ to $10) \times 10^6$.

According to SUTTON [1932] and SVERDRUP [1946], the coefficient of horizontal turbulence A depends principally on the scale of the phenomenon, such that A/r_1 equals about 0.4. Values of this ratio, entered in Table 2, are in general agreement with this result.

from data on drift bottles

r		t		r^2	$4\pi t$	Coefficient of diffusion $r^2/4\pi t = A$
ml	$\text{cm} \times 10^5$	day	$\text{sec} \times 10^5$	$\text{cm}^2 \times 10^{10}$		
60	111.0	25	21.6	12321	6.0×10^6	2.08×10^7
28	51.7	13	11.2	2673	3.8×10^6	0.70×10^7
42	77.6	53	45.8	6022	31.3×10^6	0.19×10^7
30	55.5	40	34.6	3080	19.8×10^6	0.16×10^7
20	37.0	18	15.6	1369	4.2×10^6	0.32×10^7
40	74.0	52	45.0	5476	57.1×10^6	0.10×10^7
35	64.8	45	38.9	4199	25.7×10^6	0.16×10^7
30	55.5	30	25.9	3080	23.9×10^6	0.13×10^7

Table 2--Values of A and A/r, obtained from the lateral diffusion of heat, salinity, vorticity, diatoms and drift bottles from circular sources of various radii r_1 off Southern California

Diffusing material	Year	Depth	r_1	A	A/ r_1
		m	km		
Heat	1940	0	60	5.5×10^6	0.9
	1941	50	80	2.1×10^6	0.3
Salinity	1941	0	60	2.9×10^6	0.5
	1941	50	70	1.6×10^6	0.2
Vorticity	1940	0	10	1.5×10^5	0.15
	1940	50	10	1.0×10^5	0.1
	1941	0	30	3.0×10^5	0.1
Diatoms	1941	0 to 60	25	1.8×10^6	0.7
Drift bottles	1937	0	point source	$(1.3 \text{ to } 7) \times 10^6$	...

The scale transformations used in computing A were as follows

Heat	1940	0	$0.867(8 - 14.0) = 1 - [\quad]$
	1941	50	$0.286(8 - 10.5) = 1 - [\quad]$
Salinity	1941	0	$4.000(8 - 33.0) = 1 + [\quad]$
	1941	50	$2.860(8 - 32.9) = 1 + [\quad]$
Diatoms	1941	0 to 60	$0.125(8 + 7.25) = 1 + [\quad]$

The following summary of certain conclusions regarding the related subject of the mixing length is presented here for reference. From engineering experiments the ratio of the square root of the mean square deviation of velocity to the mean velocity equals $\sqrt{u^2}/U = \gamma$, which ratio varies between 0 and 0.1, according to A. A. Kalinske, G. I. Taylor and H. L. Dryden. From the relation $\sqrt{u^2} = A/\rho \ell$,

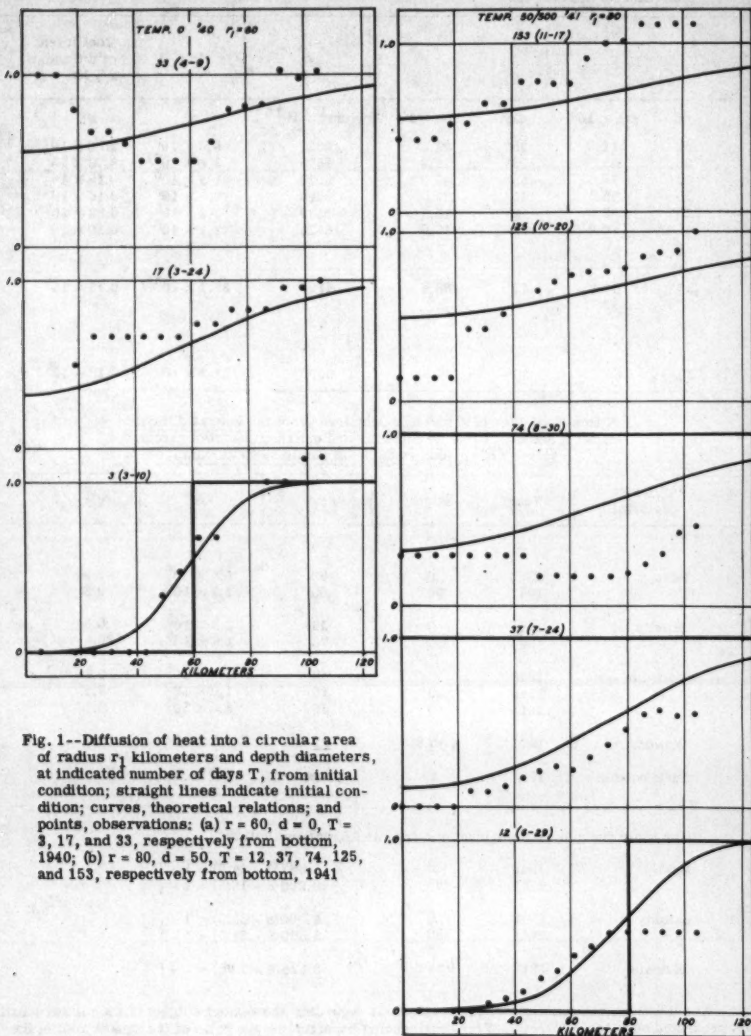


Fig. 1--Diffusion of heat into a circular area of radius r_1 kilometers and depth d meters, at indicated number of days T , from initial condition; straight lines indicate initial condition; curves, theoretical relations; and points, observations: (a) $r = 60$, $d = 0$, $T = 3, 17$, and 33 , respectively from bottom, 1940; (b) $r = 80$, $d = 50$, $T = 12, 37, 74, 125$, and 153 , respectively from bottom, 1941

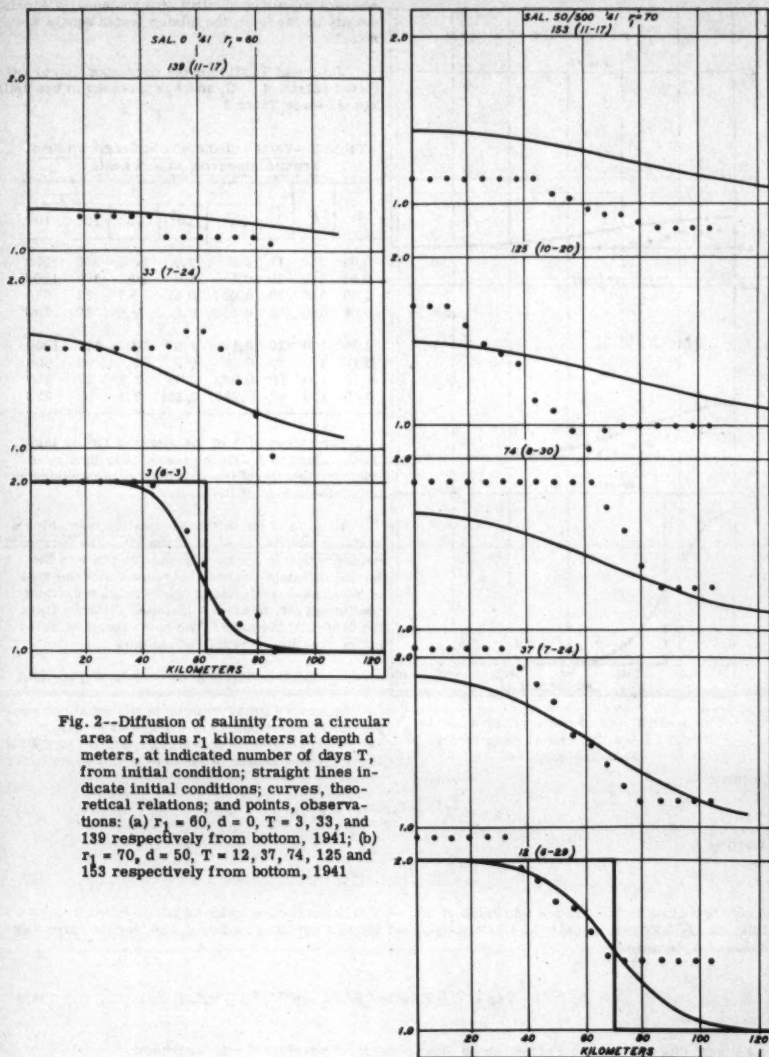


Fig. 2--Diffusion of salinity from a circular area of radius r_1 kilometers at depth d meters, at indicated number of days T , from initial condition; straight lines indicate initial conditions; curves, theoretical relations; and points, observations: (a) $r_1 = 60$, $d = 0$, $T = 3$, 33, and 139 respectively from bottom, 1941; (b) $r_1 = 70$, $d = 50$, $T = 12$, 37, 74, 125 and 153 respectively from bottom, 1941

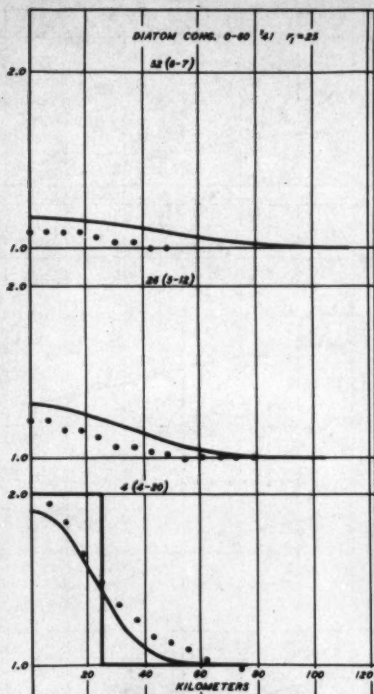


Fig. 3--Diffusion of diatoms: $r_1 = 25$, $d = 0$ to 60 , $T = 4$, 26 , and 52 respectively from bottom, 1941

solution is

$$S = S_1 [1 - e^{-r_1/Bt} (1 + r_1/Bt)] \dots (39)$$

Writing

$$S = (C/t^2) e^{-r/Bt} \dots (40)$$

and substituting in (38) proves this value of S to be a solution for any value of the constant C . The integral, $\int_0^r S(2\pi r)dr$, equals the mass of material within a circle of radius r , and, for the foregoing value of S , becomes

$$(C/t^2) \int_0^r 2\pi r e^{-r/Bt} dr = 2\pi C B^2 [1 - e^{-r/Bt} (1 + r/Bt)] \dots (41)$$

As $r \rightarrow \infty$, this approaches $2\pi C B^2$, which must equal M . Therefore $C = M/2\pi B^2$ and

$$S = M e^{-r/Bt} / 2\pi (Bt)^2 \dots (42)$$

where A equals coefficient of turbulence, ρ equals density of the fluid, the mixing length equals $\ell = A/\rho\gamma U$.

Values of ℓ , kilometers corresponding to selected values of γ , U , and A , expressed in cgs units, are shown in Table 3.

Table 3--Values of the mixing length ℓ found from engineering experiments

γ	ρ	U	A				
			10^4	10^5	10^6	10^7	10^8
0.05	1.0	10	0.2	2.0	20.	200	2000
0.05	1.0	20	0.1	1.0	10.	100	1000
0.05	1.0	30	0.087	0.87	6.7	87	870
0.05	1.0	40	0.050	0.5	5.0	50	500
0.10	1.0	10	0.1	1.0	10.	100	1000
0.10	1.0	20	0.05	0.5	5.	50	500
0.10	1.0	30	0.033	0.33	3.3	33	330
0.10	1.0	40	0.025	0.25	2.5	25	250

For values of A of the order of 10^6 or less, these values of ℓ are in general less than r , of Table 2, and therefore less than r , corresponding to points outside of the source.

Solution of the diffusion equation, assuming a variable coefficient of diffusion B --The foregoing evidence that in the open ocean the scale of the lateral diffusion process increases with the size of the area considered suggests using a variable coefficient B , where r equals the distance from the center of the area. The corresponding differential equation of radial diffusion is

$$\partial S / \partial t = B(r^2 \partial^2 S / \partial r^2 + 2 \partial S / \partial r) \dots (38)$$

An exact formal solution of the equation, subject to the same boundary conditions as before, can be expanded into convergent series [McEWEN, 1946]. At the center of the circle, $r = 0$, the exact

which is a special case of the general solution for $r_1 \rightarrow 0$. The mass of material within a circle of radius r , equals

$$M' = M[1 - e^{-r/Bt} (1 + r/Bt)] \dots \dots \dots (43)$$

Numerical applications of both (39) and (43) can be readily made by means of tables of the Poisson series used in statistics [MOLINA, 1942]. In his Table 2

$$P(c, a) = [1 - e^{-a} (1 + a)] \dots \dots \dots (44)$$

for $c = 2$, his "a" is the value of r_1/Bt in (39) or r/Bt in (43).

The square of the standard deviation equals

$$\sigma^2 = (\int_0^\infty S(2\pi r) r^2 dr) / (\int_0^\infty S(2\pi r) dr) = 6(Bt)^2 \dots \dots \dots (45)$$

for the value of S given in (42). From the same assumptions regarding times of observations as in the case of a constant coefficient of eddy diffusion

$$\sigma_0 = \sqrt{6} B T_0 = r_0/\lambda \dots \dots \dots (46)$$

$$\sigma_1 = \sqrt{6} B T_1 = r_1/\lambda \dots \dots \dots (47)$$

where $r = \lambda \sigma$ is the distance beyond which no concentration can be detected, and $\lambda \sim 1.5$. Therefore

$$B = (\sigma_T - \sigma_{T_0})/\sqrt{6} (T - T_0) = (r_T - r_{T_0})/\lambda\sqrt{6} (T - T_0) \dots \dots \dots (48)$$

which corresponds to (25) based upon a constant coefficient. Equation (48) also applies to the one-dimensional case, the initial concentration being along a plane, if the variable x , perpendicular to the surface, is substituted for r , $\sqrt{2}$ is substituted for $\sqrt{6}$, and $\lambda \sim 3.5$.

Preliminary applications of the foregoing formulas, based upon a coefficient of diffusion varying in proportion to the distance from the source, have been made with the aid of dye bombs and the observed distribution of the ammonia concentration due to the discharge of water from a sewage treatment plant. Experiments with these relatively small scale diffusion phenomena supported the theoretical relation and suggest the need of further investigations.

Concluding remarks--A simple statistical model of diffusion phenomena was found to agree with solutions of the differential equation of diffusion, and serves to interpret the coefficients in these solutions. Moreover, the statistical approach suggested alternative methods of obtaining approximate values of the diffusion coefficient from field observations, under certain restrictions regarding time and distance, on the assumption of point sources even though the actual sources were areas. Generalized solutions of the differential equation, corresponding to an initial circular area of any size, make it possible to devise a model conforming in essential features to actual conditions, for both constant and variable coefficients of diffusion. The coefficients obtained from applications of these dynamical methods involving variations with time were consistent with earlier values based upon different formulas adapted to equilibrium conditions. Since applications were made to observations averaged over periods of time, several hours or days in length, the analogy to molecular diffusion expressed by Fick's equation used a generation ago by Taylor and Schmidt, should serve in describing these ocean phenomena. In the paper by McEWEN [1948], the preliminary values of the diffusion coefficient referred to in the conclusion are too large and should be reduced to $\sim 2 \times 10^6$.

References

- BUCHANAN-WOLLASTON, H. J., On the application of the statistical theory of space distribution to hydrographic and fishery problems, *J. Consell*, v. 13, pp. 173-186, 1938.
 McEWEN, GEORGE F., Diffusion from an instantaneous circular area source (preliminary report), *Bull. Amer. Math. Soc.*, v. 52, p. 618, (abstr.), 1946.
 McEWEN, GEORGE F., The dynamics of large horizontal eddies (axes vertical) in the ocean off Southern California, *J. Mar. Res.*, v. 7, pp. 188-216, 1948.
 MOLINA, E. C., Poisson's exponential binomial limit, D. Van Nostrand, New York, 1942.
 MUNK, W. H.; EWING, G. C.; and REVELLE, R. R., Diffusion in Bikini Lagoon, *Trans. Amer. Geophys. Union.*, v. 30, pp. 59-66, 1949.
 SUTTON, O. G., Theory of eddy diffusion in the atmosphere, *Proc. R. Soc., Ser. A*, v. 135, pp. 143-

165, 1932.

SVERDRUP, H. U., Speculations on horizontal diffusion in the ocean, Scripps Institution - Hydrographic Office Project, Oceanographic Report no. 1 (unpublished), 1946.

SVERDRUP, H. U., and FLEMING, R. H., The waters off the coast of Southern California, March to July, 1937, Bull. Scripps Inst. Ocean., v. 4, pp. 261-378, 1941.

TIBBY, RICHARD B., Report on returns of drift bottles released off Southern California, 1937, Calif. Bur. Marine Fisheries, Div. of Fish and Game, Fish Bull. No. 55, 1939.

Scripps Institution of Oceanography,
La Jolla, California

(Manuscript received April 28, 1949; presented at the Thirtieth Annual Meeting, Washington, D. C., April 20, 1949; open for formal discussion until July 1, 1950.)

INTERNAL WAVES OF TIDAL CHARACTER

B. Haurwitz

(Contribution No. 477 of the Woods Hole Oceanographic Institution)

Abstract--Measurements of temperature and salinity at various depths in the ocean have shown the existence of periodic variations with the same periods as those of the tidal forces. It has been argued that these oscillations cannot be true internal waves generated by the tidal forces because the periods of free oscillations at internal discontinuities are much longer than those of the tidal forces so that the necessary resonance conditions would not seem satisfied. The argument is re-examined here, and it is shown that because of the Earth's rotation, which had not been considered previously, the periods of long internal waves are much shorter and their velocities much larger than was assumed previously. Consequently the resonance conditions for oscillations at internal surfaces of discontinuity are much more favorable than was supposed heretofore. The effect of such internal waves on the turbulent processes in the interior of the fluid is discussed.

Introduction--Observations of various oceanographic variables, such as temperature and density, have shown the existence of periodic variations whose periods are of about 12 and 24 hours' duration [SEITWELL, 1939, 1942; DEFANT, 1932, 1948]. Because of the similarity between these periods and those of the tide-generating forces it has long been assumed that these variations are due to internal wave motions of tidal character. Such internal waves in a body of water may originate either because of the existence of a surface of density discontinuity between homogeneous layers of water or because of gradual density changes with depth.

However, the possibility of true internal waves caused by tidal forces has long been considered very doubtful because, it was argued, the velocity of internal waves is much slower than that of waves of tidal character so that the necessary resonance condition for the generation of internal tidal waves does not appear satisfied. In a fluid consisting of two layers with the densities ρ^I and ρ^{II} and the depths h^I and h^{II} the velocities of long waves at the free surface, c_1 , and at the internal discontinuity, c_2 , are, to a sufficient degree of approximation

$$c_1^2 = g(h^I + h^{II}) \dots\dots\dots (1.1)$$

$$c_2^2 = g h^I h^{II} (\rho^I - \rho^{II}) / (H \cdot \rho^{II}) \dots\dots\dots (1.2)$$

The density differences are always small compared to the densities. Therefore the velocity of the internal waves (1.2) is much smaller than that of the surface waves (1.1) whose speed of propagation is in much better agreement with that of tidal waves. For this reason it was suggested by DEFANT [1932, pp. 295-298] that internal variations of the oceanographic variables with periods equal to those of the tidal forces are not strictly internal waves, but rather due to the variations of the tidal currents with time which cause periodic variations of the inclinations of an existing surface of discontinuity.

However, a closer investigation shows that the foregoing argument does not hold because in the above expressions for the wave velocity the Earth's rotation is neglected. This simplification is not justified when waves of the large dimensions of tidal oscillations are considered. When the Earth's rotation is taken into account the phase velocity c of long waves of wave length L in a homogeneous layer of depth H on a disk rotating with the angular velocity $\lambda/2$ becomes

$$c^2 = \lambda^2 L^2 / 4\pi^2 + gH \dots\dots\dots (1.3)$$

where g is the acceleration of gravity [SVERDRUP, 1926]. It will be shown that the square of the phase velocity of internal waves is increased by the same term depending on λ and L so that internal waves of great length have much larger velocities if the fluid is rotating than if it is at rest. Their speed does therefore approach that of tidal waves much more closely than in a non-rotating system so that the existence of true internal waves of tidal character seems possible.

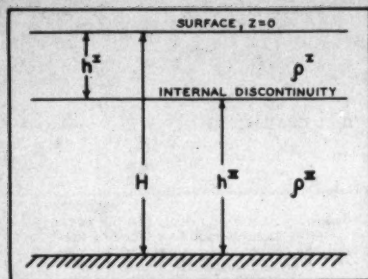


Fig. 1--Sketch showing terms in two-layer density problem

The equations of the problem--It will be assumed that the fluid consists of two layers of the densities ρ^I and ρ^{II} where the superscript I refers to the upper layer, II to the lower layer, $\rho^I < \rho^{II}$ (see Fig. 1). The fluid is bounded by a lower rigid boundary, $z = -H$, and by a free upper surface, $z = 0$. As long as no wave motion takes place the fluid is at rest so that its state is described by the hydrostatic equation

$$dP/dz = -g\rho \dots \dots \dots (2.1)$$

Here P represents the pressure in the absence of perturbation motions. Since such an equation holds both for the upper and the lower layer the superscripts have been omitted.

It will be assumed that a tidal force with the potential

$$\Omega = M \exp [i(\mu x - \gamma t)] \dots \dots \dots (2.2)$$

acts on the fluid. Here, $\mu = 2\pi/L$ where L is the wave length, $\gamma = 2\pi/T$ where T is the period, and M is a constant. Further the wave velocity

$$c = \gamma/\mu = L/T$$

Since the fluid is unbounded in the horizontal direction these motions can be assumed as independent of the y -coordinate, that is of the horizontal direction perpendicular to the direction of wave propagation. Because of the large dimensions of tidal waves the customary approximations can be made, namely that the horizontal motions and the perturbation pressure are independent of the depth and that hydrostatic equilibrium in the vertical is preserved. The latter condition implies that the vertical accelerations can be neglected (quasistatic motion) so that the perturbation pressure is completely determined by the deviations of the free and internal surfaces, ζ_0 and ζ_1 , respectively, from their equilibrium values. Thus, the perturbation pressure in the upper layer

$$p^I = g\rho^I\zeta_0 \dots \dots \dots (2.3)$$

and in the lower layer

$$p^{II} = g\rho^I\zeta_0 + g(\rho^{II} - \rho^I)\zeta_1 \dots \dots \dots (2.4)$$

The equations of motion for the two layers may therefore be written in the following form

$$\partial u^I/\partial t - \lambda v^I = -g\partial\zeta_0/\partial x - \partial\Omega/\partial x \dots \dots \dots (2.5)$$

$$\partial v^I/\partial t + \lambda u^I = 0 \dots \dots \dots (2.6)$$

$$\partial u^{II}/\partial t - \lambda v^{II} = -g(\rho^I/\rho^{II})(\partial\zeta_0/\partial x) - g[(\rho^{II} - \rho^I)/\rho^{II}](\partial\zeta_1/\partial x) - \partial\Omega/\partial x \dots \dots \dots (2.7)$$

$$\partial v^{II}/\partial t + \lambda u^{II} = 0 \dots \dots \dots (2.8)$$

Here $\lambda = 2\omega \sin \phi$ where ω is the angular velocity of the Earth's rotation, ϕ the latitude. From the equation of continuity one obtains by integration, since u is independent of z , for the upper layer

$$\partial\zeta_0/\partial t - \partial\zeta_1/\partial t = -h^I\partial u^I/\partial x \dots \dots \dots (2.9)$$

and for the lower layer

$$\partial\zeta_1/\partial t = -h^{II}\partial u^{II}/\partial x \dots \dots \dots (2.10)$$

The integration is here taken for each layer between the undisturbed positions of the respective boundaries. This simplification is consistent with the degree of approximation used in the discussion of small perturbations.

It may now be assumed that the quantities $u^I, v^I, \zeta_0^I, \zeta_1^I, u^H, v^H, \zeta_1^H$ contain the same periodicity factor as the tidal potential Ω , namely $i(\mu x - \gamma t)$. Then the velocity components can be expressed by ζ_0^I and ζ_1^I with the aid of (2.6), (2.8), (2.9) and (2.10). Thus,

$$u^I = c(\zeta_0^I - \zeta_1^I)/h^I \dots \dots \dots (2.11)$$

$$v^I = -i\lambda(\zeta_0^I - \zeta_1^I)/\mu h^I \dots \dots \dots (2.12)$$

$$u^H = c\zeta_1^H/h^H \dots \dots \dots (2.13)$$

$$v^H = -i\lambda\zeta_1^H/\mu h^H \dots \dots \dots (2.14)$$

If these expressions are introduced in (2.5) and (2.7) the following two equations are obtained for ζ_0^I and ζ_1^I ,

$$[(c^2 - \lambda^2/\mu^2)/h^I - g]\zeta_0^I - [(c^2 - \lambda^2/\mu^2)/h^I]\zeta_1^I = \Omega \dots \dots \dots (2.15)$$

$$-g\rho^I\zeta_0^I\rho^H + \zeta_1^I[(c^2 - \lambda^2/\mu^2)/h^H - g(1 - \rho^I/\rho^H)] = \Omega \dots \dots \dots (2.16)$$

If the periodicity factors are cancelled on both sides of (2.15) and (2.16) the amplitudes of ζ_0^I and ζ_1^I can be determined in terms of the amplitude of Ω . Since the distinction between the various variable quantities and their amplitudes is not important the same letter will be used to denote both.

Velocities of the free waves—If the tidal force is absent, $\Omega = 0$ the system of (2.15) and (2.16) is homogeneous and its determinant Δ must vanish if ζ_0^I and ζ_1^I are not to be both zero,

$$\Delta = (c^2 - \lambda^2/\mu^2)^2/h^I h^H - g(1/h^I + 1/h^H)(c^2 - \lambda^2/\mu^2) + g^2(1 - \rho^I/\rho^H) = 0 \dots \dots (3.1)$$

This quadratic equation in $(c^2 - \lambda^2/\mu^2)$ gives the wave velocity in the case of free oscillations of the fluid system. Since the percentual density difference $1 - (\rho^I/\rho^H)$ is very small the two roots are, with sufficient approximation

$$c^2 = \lambda^2/\mu^2 + gH[1 - (h^I h^H/H^2)(1 - \rho^I/\rho^H)] \dots \dots \dots (3.2)$$

$$c^2 = \lambda^2/\mu^2 + gh^I h^H(1 - \rho^I/\rho^H)/H \dots \dots \dots (3.3)$$

The first root is practically the same as the wave velocity in a single layer of depth H since the bracket is very nearly equal to unity. The right-hand side of (3.3) represents the square of the velocity of free waves at an internal surface of discontinuity if the two fluid layers are relatively shallow. It will be seen that in the case of rotating fluid the wave velocity is considerably increased. A formula similar to (3.3) has been given by DEFANT [1932, p. 301]. But since it was written in a different form its bearing on the present problem was not recognized.

To give a numerical example let $h^I = 200$ m, $h^H = 2800$ m, $\lambda = 10^{-4}$ which corresponds to a latitude of 43° ; further let $1 - (\rho^I/\rho^H) = 3 \times 10^{-2}$. This density discontinuity is about ten times larger than those ordinarily encountered in the sea. This large value has been chosen to demonstrate more clearly the relative effects of the Coriolis term and of the density-discontinuity term. With a wave length of 14,600 km, which is the wave length of the semidiurnal progressive tide at 43° , the internal-wave velocity would be in the absence of rotation 7.4 m/sec, while with rotation it is 232 m/sec. The velocity of the wave at the free surface would be 171 m/sec in the absence of the Earth's rotation and 288 m/sec when the Earth's rotation is taken into account. Thus, for internal waves whose lengths are similar to those of tidal waves the term due to the Earth's rotation is much more important than that due to the density difference. Furthermore, the velocity of the internal wave approaches rather closely that of the surface wave with increasing wave length because in both cases the Coriolis term is predominant.

The periods of the waves at the free surface, T_0 , and at the internal discontinuity, T_1 , are given by

$$T_0 = (2\pi/\lambda)(1 + 4\pi^2 gH/L^2 \lambda^2)^{-1/2} \dots \dots \dots (3.4)$$

$$T_1 = (2\pi/\lambda)[1 + 4\pi^2 gh^I h^H(1 - \rho^I/\rho^H)/L^2 H \lambda^2]^{-1/2} \dots \dots \dots (3.5)$$

These expressions show that for very short waves the period is not affected appreciably by the Earth's rotation, but with increasing wave lengths the period tends to the limit of half a pendulum day. The

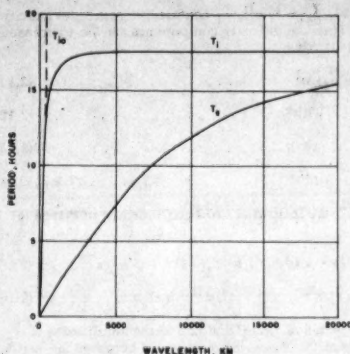


Fig. 2--Relationship of wavelength to period

quantitative check on the resonance effect. Nevertheless, it shows that the influence of the Earth's rotation is in the right direction, namely towards a substantial decrease in the length of the period and a corresponding increase in the wave velocity so that these two quantities come at least closer towards the magnitude required for resonance. For a quantitative check on the possibility of resonance the spherical shape of the fluid layers cannot be neglected.

Amplitudes of the oscillating surfaces--If the tidal force is taken into account it follows from (2.15) and (2.16) that

$$\mathcal{F}_0 = [H(c^2 - \lambda^2/\mu^2)/h^2 \Pi - g(1 - \rho^I/\rho^II)]\Omega/\Delta \quad (4.1)$$

$$\mathcal{F}_1 = [(c^2 - \lambda^2/\mu^2)/h^2 - g(1 - \rho^I/\rho^II)]\Omega/\Delta \quad (4.2)$$

$$\mathcal{F}_0/\mathcal{F}_1 = 1 - [h^2(c^2 - \lambda^2/\mu^2)/h^2 \Pi] / [gh^2(1 - \rho^I/\rho^II) - (c^2 - \lambda^2/\mu^2)] \quad (4.3)$$

This formula is identical with that of DEFANT [1932, p. 297] for the amplitude ratio in a non-rotating fluid except that $c^2 - \lambda^2/\mu^2$ appears here instead of c^2 .

The most characteristic feature of internal waves is that the vertical amplitude has a maximum at the internal discontinuity. Therefore the amplitude ratio $\mathcal{F}_0/\mathcal{F}_1$ must be less than one for internal waves. This condition is satisfied if

$$c^2 - \lambda^2/\mu^2 \leq gh^2 \Pi (1 - \rho^I/\rho^II)/H \quad (4.4)$$

If the effects of rotation on the wave velocity are omitted this inequality leads to a very small velocities as shown above in the numerical example for (3.3). Since tidal waves have much larger velocities it would seem that no internal tidal waves could exist as long as the effect of rotation is disregarded. However, the rotation permits the occurrence of much larger velocities, as shown in the same example, leading again to the conclusion that internal waves of tidal character appear possible. For a quantitative test it would be necessary to extend the investigation to spherical fluid layers, as pointed out before.

If the velocity of the waves is that given by (3.2) or (3.3), Δ vanishes. In this particular case, both the amplitudes $\mathcal{F}_0$ of the free surface and $\mathcal{F}_1$ of the internal boundary increase with time. This is the case of resonance. In reality the amplitudes would, of course, remain finite even in this case because of friction.

The ratio of the amplitudes $\mathcal{F}_0/\mathcal{F}_1$ remains finite even if friction is not considered. If the value

conditions are illustrated in Figure 2, which gives the periods of surface waves T_0 , internal waves T_1 , and internal waves in the absence of the Earth's rotation T_2 for two fluid strata whose densities and depths have been given above. It will be seen that with increasing wave length the period of the internal wave increases rapidly if the effect of the Earth's rotation is neglected, while in rotating fluid layers the period approaches half a pendulum day. For standing oscillations at an internal discontinuity DEFANT [1940] has shown that the free period tends towards half a pendulum day if the horizontal dimensions of the stratified oscillating system are sufficiently large. A marked reduction of the period of internal waves due to the rotation has been found also for spherical layers for the atmosphere [HAURWITZ, 1937, p. 214].

If waves are to be generated by the tidal force the period of the free oscillation must be very nearly, within a few minutes, equal to that of the tidal force. Only then can the resonance effect become important. Otherwise the amplitudes of the forced oscillations remain insignificant. The plane fluid model considered here is too crude to permit a

(3.2) for the wave velocity at the free surface is introduced in (4.3)

$$\zeta_0/\zeta_1 = H/h\Pi, \text{ approximately}$$

as should be expected for the surface wave. Insertion of (3.3) for the internal wave in (4.3) leads to

$$\zeta_0/\zeta_1 = 0, \text{ approximately}$$

so that the free surface is practically unaffected by the internal wave.

Horizontal velocities and vertical displacements.-- The velocity components in the horizontal plane are expressed by the vertical displacements of the two boundaries, ζ_0 and ζ_1 , in (2.11) to (2.14). In order to make them more easily comparable with each other it is convenient to express them either by ζ_0 or ζ_1 as can be done with the aid of (4.3). Here the displacement of the internal boundary, ζ_1 , will be used so that

$$u^I = \zeta_1 c(c^2 - \lambda^2/\mu^2)/h^I h\Pi [(c^2 - \lambda^2/\mu^2)/h^I - g(1 - \rho^I/\rho\Pi)] \dots (5.1)$$

$$v^I = -\zeta_1 \lambda(c^2 - \lambda^2/\mu^2)/\mu h^I h\Pi [(c^2 - \lambda^2/\mu^2)/h^I - g(1 - \rho^I/\rho\Pi)] \dots (5.2)$$

while the corresponding expressions for the lower layer remain unchanged,

$$u^{II} = c \zeta_1/h\Pi \dots (2.13)$$

$$v^{II} = -\lambda \zeta_1/\mu h\Pi \dots (2.14)$$

If the wave velocity corresponds to that of the free surface wave, (3.2),

$$u^I = \zeta_1 c/h\Pi \dots (5.3)$$

$$v^I = -\lambda \zeta_1/\mu h\Pi \dots (5.4)$$

that is the horizontal velocity is uniform throughout the whole layer, as is to be expected. If the wave velocity corresponds to that of the free internal wave

$$u^I = -\zeta_1 c/h^I \dots (5.5)$$

$$v^I = \lambda \zeta_1/\mu h^I \dots (5.6)$$

that is the horizontal velocities are opposite in both layers and such that the net mass transport through a plane perpendicular to the horizontal velocity and extending through the whole fluid is zero, as it should be in order to satisfy the continuity condition. This result is, of course, only an approximation which does not take into account the small perturbations of the free and internal surfaces and the small density difference between both layers.

The vertical displacements ζ at other depths than at the free and internal surfaces can be determined from the equation of continuity

$$\partial w / \partial z = -\partial u / \partial x$$

If this equation is integrated from the level $z = -h^I$ to an arbitrary level z within the first layer it follows that

$$w^I = w_1^I - (z + h^I) \partial u^I / \partial x$$

Here w_1^I denotes the vertical velocity at the internal boundary. By integration with respect to time

$$\zeta^I = \zeta_1 + (z + h^I) u^I / c \dots (5.7)$$

Similarly for the second layer

$$\zeta^{II} = (z + H) u^{II} / c \dots (5.8)$$

These equations show that the vertical displacement is a linear function of the elevation. In order to express ζ^I and ζ^{II} by the vertical displacement of the internal boundary equations (5.1) and (2.13)

may be used. If in particular c is equal to the velocity of the free wave at the free surface

$$\zeta^I = \zeta^H = \int_1 (z + H)/h^H$$

In this case the vertical displacement decreases linearly from its value at the free surface to zero at the bottom of the sea. If c equals the velocity of the free wave at the internal boundary

$$\zeta^I = -\int_1 z/h^I$$

$$\zeta^H = \int_1 (z + H)/h^H$$

The vertical displacement has now its maximum at the internal boundary and decreases linearly to the free surface and to the ocean bottom.

Concluding remarks-- The observations show clearly the occurrence of internal waves whose periods coincide with the tidal periods, and the foregoing discussion suggests that such internal tidal waves are theoretically possible. The amplitudes of these internal waves are as a rule much larger than those of surface waves because the potential energy of an internal wave at the boundary between two fluids of almost equal density is much smaller than that of a surface wave of the same dimensions. DEFANT [1948] has even shown observations which are strongly suggestive of a breaking of these internal waves. A satisfactory explanation of this phenomenon has not yet been given. It may be due to shearing instability at the discontinuity because the tidal currents in the upper and the lower layer are in opposite directions according to (5.3) to (5.6), and the shear may be strong enough to overcome the stabilizing effect of the stratification. Another possible explanation might be based upon interference between a surface wave and an internal wave. If two such waves are in phase or very nearly in phase at a given locality their superposition will produce a stronger effect than either of the two waves alone. A decision as to whether one of these two explanations is correct will require considerably more data and further theoretical studies.

Such internal waves must contribute appreciable to the internal mixing in the ocean since the tidal currents in the two layers are in opposite directions. Consequently the original sharp surface of discontinuity must be transformed into a zone of gradual transition where the properties of both layers are being mixed rapidly.

Since these discontinuity surfaces and therefore the internal waves are mainly situated in the uppermost regions of the sea they may also be of importance for submarine navigation and require further study in this connection.

Acknowledgment-- This research was in part carried out with the support of Contract N6onr-277 with the Office of Naval Research.

References

- DEFANT, A., Die Gezeiten und Inneren Gezeitenwellen des Atlantischen Ozeans, *Wiss. Ergeb. Meteor.*, 1925-1927, v. 7, part 1, 318 pp., 1932.
 DEFANT, A., Die ozeanographischen Verhältnisse während der Ankerstation des *Altair* am Nordrand des Hauptstromstriches des Golfstromes Nördlich der Azoren, *An. Hydr. Marit. Met.*, v. 68, November Beiheft, 35 pp., 1940.
 DEFANT, A., Über interne Gezeitenwellen und ihre Stabilitätsbedingungen, *Arch. Met. Geophys. Bioklimat.*, v. 1, pp. 39-61, 1948.
 HAURITZ, B., The oscillations of the atmosphere, *Gerl. Beitr. Geophys.*, v. 51, pp. 195-233, 1937.
 SEIWELL, H. R., The effect of short period variations of temperature and salinity on calculations in dynamic oceanography, *Pap. Phys. Ocean. Met.*, v. 7, no. 3, 32 pp., 1939.
 SEIWELL, H. R., An analysis of vertical oscillations in the southern North Atlantic, *Proc. Amer. Phil. Soc.*, v. 85, pp. 136-158, 1942.
 SVERDRUP, H. U., Dynamic of tides on the North Siberian Shelf, *Geofys. Publ.*, v. 4, no. 5, 75 pp., 1926.

College of Engineering,
 New York University, New York, N. Y., and
 Woods Hole Oceanographic Institution,
 Woods Hole, Massachusetts

(Manuscript received June 1, 1949; presented at the Thirtieth Annual Meeting, Washington, D. C., April 20, 1949 as part of the Symposium on Turbulence and Mixing in the Sea; open for formal discussion until July 1, 1950.)

THE TEMPERATURE IN AN ACCRETING EARTH

A. E. Benfield

Abstract--The temperature at the surface of an accreting Earth is discussed; it is concluded that the surface is likely to be molten during the later stages of the process. The effect of pressure alone in raising the temperature in the deep interior is also considered; this effect appears to be inadequate to cause melting, but no definite conclusion is drawn, as numerous uncertainties enter into this calculation.

Introduction--In a recent paper URRY [1949] has drawn attention to the fact that in earlier ages the radioactive elements of the Earth were more abundant than at present. By making use of the known half-life times of the naturally occurring radioactive elements he has been able to show that two or three billion years ago these elements generated appreciably more heat in the Earth than they do today. In conjunction with G. Comenetz, he has made various calculations, including the variation with time of the flow of heat to the surface of the Earth both for the past and for the future.

In his paper, however, Urry suggests the possibility of the Earth having had a dust-cloud origin as a solid body about seven billion years ago, with a subsequent rebirth as a molten body at a later date, believing that the larger amount of heat generated long ago by the radioactive elements in the Earth could have melted it. This suggestion is somewhat radical. An age of seven billion years for the Earth is about twice as great as is nowadays generally thought to be likely. Astrophysical considerations suggest, at present, an age of the stars in our galaxy of about five billion years [BONDI and GOLD, 1948], though a greater age is not out of the question. (Urry, for example, draws attention to the fact that some measurements of the helium content of meteorites suggest ages as great as seven billion years. The reliability of these measurements has, however, been doubted [BAUER, 1947].) There is some doubt whether such a melting as Urry suggests could have proceeded all the way to the surface of the Earth, which is continually losing heat by conduction from the interior.

This paper, therefore, will seek to examine the possibility that the Earth, if it formed by accretion, did so as a molten body rather than as a solid. It will be shown that one probably need not suppose the age of the Earth to be seven billion years in order for its surface to have been molten; and an attempt will be made to estimate the effect of the increasing pressure of overlying layers of the Earth, during accretion, in raising the temperature of its interior.

In what follows, we shall first consider the rise of temperature at the surface of an accreting planet resulting from the dissipation of the kinetic energy of the incoming material, and later we shall discuss the effect of the increasing pressure on the temperature in the interior.

The temperature at the surface--It is generally conceded that a planet forming by the aggregation of gas or small solid particles must begin its growth slowly, and that no appreciable rise in the temperature of its surface will occur until the planet is of such a size that it creates at least a modest gravitational field in its neighborhood. At this stage, however, the kinetic energy of impact of the incoming material may become appreciable; this energy will be used in the following ways: (1) in raising the temperature of the incoming material, including possible changes of state; (2) as radiation back into outer space; (3) in warming the interior of the planet by conduction or convection from the surface. The third category above may certainly be neglected while the surface is still solid, and perhaps also if it is molten.

Considering, then, the first two items of the preceding paragraph we may write the differential equation

$$[(\rho_0 GM/r) - c\rho_0 (T - T_0) - L\rho_0]dr/dt = \sigma T^4 \dots \dots \dots (1)$$

in which the symbols are as follows:

ρ_0 , the density at the Earth's surface, taken as 3 gm/cm³
 G , the universal gravitational constant, 6.67×10^{-8} cgs

M , the present mass of the Earth, 6×10^{27} gm
 r , the present radius of the Earth, 6.4×10^8 cm
 c , the specific heat of the material of the planet's surface
 T , the temperature of the Earth's surface, in $^{\circ}\text{K}$
 T_0 , the temperature of the incoming material as it enters the Earth's gravitational field, in $^{\circ}\text{K}$
 L , the energy associated with a change of phase of the material of the Earth's surface
 t , time
 σ , Stefan's Constant, 5.72×10^{-5} ergs/cm² sec $^{\circ}\text{C}^4$

The first term on the left of (1) represents the kinetic energy of the incoming material, the second term is the energy needed to raise its temperature from T_0 to T , the third term is the energy used in changes of phase, say from a solid to a liquid state. The right hand term is the energy radiated into space.

If we consider the Earth with its present size the term $\rho_0 GM/r$ amounts to about 2×10^{12} ergs/cm³, while for a rise in temperature $T - T_0 = 2000^{\circ}\text{K}$, the term $c\rho_0(T - T_0)$ amounts only to about 7×10^{10} ergs/cm³. Furthermore, if we assign a value of 500 joules/gm to L , the term $L\rho_0$ is a mere 1.5×10^{10} erg/cm³. (This value of L is larger than the heat of fusion of most minerals.) Therefore, for the later stages of growth by accretion, in which we are interested here, the second two terms of the left hand side of (1) may be neglected. We are left, therefore, with

$$(\rho_0 GM/r)dr/dt = \sigma T^4 \dots \dots \dots (2)$$

which can be solved for T if we can find the proper value for dr/dt . This problem has been considered by TER HAAR and WERGELAND [1948], and TER HAAR [1948] has made a careful study of the ideas of VON WEIZSÄCKER [1943] on the formation of the solar system. Ter Haar and Wergeland start with a different differential equation from (1) but, after making some approximations, end with an equation which differs in form but is in fact the same as (2). Ter Haar does not directly compute dr/dt , but rather uses a relation $dM/dt = \alpha M^2$ where α is a constant which he calculates from astrophysical considerations to be 2×10^{-41} gm⁻¹ sec⁻¹; as a result he estimates for the final stage of the Earth's accretion a surface temperature between 1000°K and 2000°K , pointing out that he believes there are reasons for this to be a low figure, and that a temperature of 4000°C would not be unreasonable. Later (private communication) he says that he believes a more trustworthy value of α to be 100 times greater than the value used in his published estimate; this leads to a value of 3500°K for the temperature of the Earth's surface at the end of its accretion.

HOYLE [1946], who has considered the question of the condensation of the planets from a somewhat different point of view, also remarks that the temperature at the surface will be adjusted so that the rate of loss of energy by radiation is approximately equal to the rate of supply of energy due to the infall of accreted material. For a planet of mass 10^{26} gm he calculates a surface temperature of 2000°K and states that the temperatures will be sufficiently high for masses of the order of the terrestrial planets to become liquid, though it seems likely that he refers to the surfaces of these planets rather than meaning to imply that the deep interior will also be molten.

It seems, therefore, that according to our present ideas and information the outer part of the Earth, should it have formed by accretion, could have been in a molten condition as the process of formation approached its end, and that there is no need to extend the age of the Earth to seven billion years in order to account for its superficial characteristics. Harold C. Urey has, however, recently told me that he believes that the relation $dM/dt = \alpha M^2$ may not apply to the formation of the Earth; the high surface temperatures found by Ter Haar and Hoyle may, therefore, need some reduction.

The temperature rise due to compression in the interior--The fact that the increase of pressure during a process of accretion will cause a rise of temperature in the interior of the Earth seems to have been first mentioned by CHAMBERLIN [1916, p. 164] who, however, does not appear to have made any quantitative estimate of it. (The possible importance of this effect was drawn to my attention by F. Whipple.) This is perhaps not surprising, as our knowledge of the behavior of materials at the pressures existing deep in the interior of the Earth can even now only be inferred by a considerable extrapolation, and at the time Chamberlin wrote a great deal of the high pressure work of P. W. Bridgman was not yet begun. Besides, the nature of the material at the center of the Earth is still uncertain. For instance, it has recently been suggested by RAMSEY [1948, 1949] that the Earth's core is not an alloy of iron and nickel, as many believe, but a metallic phase of the same chemical substance as constitutes the mantle; the change from a molecular to a metallic phase is thought to be the result of pressure. Therefore, what follows below will be a rough estimate based on inadequate knowledge, and it seems likely that the figures derived will be changed, perhaps radically, as our knowledge grows.

Of the many factors involved, the one quantity known with moderate accuracy is the pressure at various depths in the Earth. We shall, accordingly, start with a pressure P of 3.5×10^{12} dynes/cm² at the center of the Earth [BIRCH, 1942, p. 105], and attempt to calculate the rise in temperature caused by compression to this pressure. ZEMANSKY [1943, p. 225] gives an expression for the rise in temperature, due to a reversible adiabatic process, which may be written

$$dT = (\beta T / \rho C_p) dP \dots \dots \dots (3)$$

where $\beta = (1/V)(\partial V / \partial T)_P$, which is the coefficient of thermal expansion by volume, V ; C_p is the specific heat at constant pressure of the compressed material and ρ is its density. The adiabatic condition is probably adequately satisfied in the deep interior of the Earth, since the processes whereby heat is lost to the surface operate slowly [SLICHTER, 1941], compared with the 10^8 or 10^9 years during which the process of accretion is thought to become complete. The condition of reversibility is satisfied with less certainty; changes of phase may introduce irreversibility, as would also any effect of hysteresis. However, we shall assume that there is no irreversibility, realizing that this assumption possibly introduces an appreciable error.

As the change of temperature will not be infinitesimal, we shall integrate (3), assuming for the moment that C_p , ρ , and β are all constants during the process of compression. This assumption introduces a further uncertainty into the results of this calculation. The variations of C_p , ρ , and β with temperature and pressure are discussed below. The result of the integration is

$$\log_e T = \beta P / \rho C_p + \log_e T_0 \dots \dots \dots (4)$$

We shall now try to find reasonable values for the right hand side of (4).

The value of P has been mentioned above. The value of T_0 is uncertain; writers interested in planetary accretion usually assume that, at the beginning of the process, the Sun was much as it is today, and that the temperature of the first condensing material was close to that of the planet's present surface temperature. Thus, a simple calculation based on the work of HOYLE [1946] suggests a value of $T_0 = 450^\circ\text{K}$ for the Earth. Ter Haar (private communication) suggests 300°K . Calculations based on the work of VON WEIZSÄCKER [1943, p. 319] suggest a value closer to 250°K . The effect of T_0 on T is considerable, and in making our estimate of T it will be wise to study the effect of setting T_0 equal to various values.

In trying to choose a reasonable value of C_p , we note that BIRCH [1942] gives values for the heat capacity of various igneous rocks in the temperature range from 0°C to 800°C , the variation being from about 0.7 to 1.2 joules/gm $^\circ\text{C}$. The variation of C_p with pressure is less well known. ZEMANSKY [1943, p. 237] states that C_p for liquids and solids is extremely insensitive to pressure, and he gives figures for mercury showing a decrease of less than 0.2 per cent when the pressure is increased to about 7×10^9 dynes/cm². BRIDGMAN [1931, pp. 174-175] discusses the variation of C_p with pressure for solid metals, pointing out that it almost always decreases with increasing pressure, though very slowly. His measurements suggest that C_p will not be reduced to a small fraction of its value at atmospheric pressure until the pressure has risen to about 10^{14} or 10^{15} dynes/cm². This pressure far exceeds that at the center of the Earth. We shall assume that rocks behave in a similar way, and that the effect of pressure on C_p is negligible. Thus, on the basis of what is known, we shall at this stage pick for our calculations a value of $C_p = 1.0 \times 10^7$ ergs/gm $^\circ\text{C}$. This is close to the value of 0.2 cal/gm $^\circ\text{C}$ used by JEFFREYS [1929, p. 139] in making a somewhat related calculation.

The value of the coefficient of thermal expansion, β , is affected oppositely by increasing temperature and increasing pressure. The effects, unfortunately, are not small. For instance, for various glasses, BIRCH [1942, p. 37] shows that at 1200°C the value is some four times as great as at 20°C . For igneous rocks in the temperature range 20°C - 100°C , he gives values with a mean of 6.8×10^{-6} for the linear coefficient of expansion, which may be multiplied by three to give an estimate of the cubical coefficient. The effect of pressure is to decrease the coefficient. Thus, for mercury, ZEMANSKY [1943, p. 239] shows that the cubical coefficient at a pressure of about 7×10^9 dynes/cm² is 84 per cent of its value at atmospheric pressure. BRIDGMAN [1940] has studied the alkali halides and finds that at a pressure of about 5×10^{10} dynes/cm², in the temperature range of -80°C to $+20^\circ\text{C}$, the coefficients have an average value of 47 per cent of their atmospheric value, though there is considerable scatter from one halide to another. As the effect of pressure seems likely to be greater than the effect of temperature for the case in hand, we shall choose a value of $\beta = 15 \times 10^{-6}$ $^\circ\text{K}^{-1}$ for an average value during the process of compression.

Substituting these values into (4), using a mean density of 7.5 gm/cm³, and setting $T_0 = 250^\circ\text{K}$, we find a temperature at the center of the Earth of about 500°K . If we set $T_0 = 450^\circ\text{K}$, the central

temperature is 900°K. If we suppose the initial temperature T_0 to be as high as 1000°K, the central temperature becomes 2000°K. Thus, the temperature at the center is roughly double the temperature T_0 of the material before compression.

The following somewhat more elaborate method of making these calculations is perhaps a little less approximate, and is worth carrying out in order to see by how much the results differ from those given in the preceding paragraph. We have seen that C_p appears to be much more strongly a function of temperature than of pressure. We shall, therefore, write $C_p = a + bT$, where a and b are constants having the values 5×10^6 ergs/gm °K and 6.7×10^3 ergs/gm °K² respectively. We shall similarly assume ρ to be a linear function of pressure alone, and write $\rho = \rho_0 + kP$, where ρ_0 and k are constants with the values 3 gm/cm³ and 2.57×10^{-12} gm/erg respectively. For lack of better information we shall consider β to be the same constant as before.

If we insert these linear expressions for C_p and ρ into (3) and integrate, we find that

$$a \log_e T + bT = (\beta/k) \log_e (\rho_0 + kP) + a \log_e T_0 + bT_0 - (\beta/k) \log_e \rho_0 \dots (5)$$

which may be solved for T for various values of T_0 . If we set $T_0 = 250^\circ\text{K}$, 450°K and 1000°K , as before, and let $P = 3.5 \times 10^{12}$ dynes/cm², we now find that $T = 700^\circ\text{K}$, 1000°K and 1800°K respectively. (If these last calculations are repeated, assuming β to be a constant twice as large as before, that is, 30×10^{-6} °K⁻¹, the three temperatures become respectively 1400°K , 1800°K and 2700°K . This calculation gives a measure of the change in T caused by a large error in β .) Therefore, these calculations give values of T which do not differ significantly from those found above using the simpler (4).

The melting point of rocks at a pressure of 3.5×10^{12} dynes/cm² is, like everything else, uncertain. (In this connection it is perhaps worth mentioning a recent paper by GUTENBERG [1949], which is concerned with approximations in geophysics, in which he reminds us that it is possible that the laws of physics have changed in the time since the Earth was created.) JEFFREYS [1929] discusses the increase of melting point with pressure, and shows that its rate of increase is apt to grow less as the pressure increases. A melting point of about 2000°K at great depth is perhaps not unreasonable. Thus, we see that our estimates of the effect of pressure suggest that it alone, without for instance the help of radioactive heat, is inadequate to cause melting at the center of the Earth, though our knowledge is too incomplete to draw a certain conclusion.

Conclusions--It seems likely that the outer part of an accreting planet like the Earth will be molten towards the end of its growth. The effect of pressure alone, however, seems to be inadequate to cause melting in the interior, though the estimation of the rise in temperature caused by compression rests on approximate calculations.

Acknowledgments--It is a pleasure to thank C. H. Berry, F. Birch, H. C. Urey, and F. Whipple for discussions and help.

References

- BAUER, C. A., Production of helium in meteorites by cosmic radiation, *Phys. Rev.*, v. 72, pp. 354-355, 1947.
- BIRCH, F. (ed), *Handbook of physical constants*, Geol. Soc. Amer., Spec. Pap. 36, 325 pp., 1942.
- BONDI, H., and GOLD, T., The steady-state theory of the expanding universe, *Mon. Not. R. Astron. Soc.*, v. 108, pp. 252-270, 1948.
- BRIDGMAN, P. W., *The physics of high pressure*, Macmillan Co., 398 pp., 1931.
- BRIDGMAN, P. W., The compression of 46 substances to 50,000 kg/cm², *Proc. Amer. Acad. Arts Sci.*, v. 74, no. 3, pp. 21-51, 1940.
- CHAMBERLIN, T. C., *The origin of the Earth*, Univ. of Chicago Press, 271 pp., 1916.
- GUTENBERG, BENO, Approximations in geophysics, *Veröffent. Finn. Geod. Inst.*, no. 36, pp. 41-44, 1949.
- HOYLE, F., On the condensation of the planets, *Mon. Not. R. Astron. Soc.*, v. 106, pp. 406-422, 1946.
- JEFFREYS, H., *The Earth*, Cambridge Univ. Press, 2nd ed., 339 pp., 1929.
- RAMSEY, W. H., On the constitution of the terrestrial planets, *Mon. Not. R. Astron. Soc.*, v. 108, pp. 406-413, 1948.
- RAMSEY, W. H., On the nature of the Earth's core, *Mon. Not. R. Astron. Soc. (Geophys. Suppl.)*, v. 5, pp. 409-426, 1949.
- SLICHTER, L. B., Cooling of the Earth, *Geol. Soc. Amer., Bull.*, v. 52, pp. 561-600, 1941.
- TER HAAR, D., Studies on the origin of the solar system, *Kgl. Danske Vidensk. Sels. Matematisk-Fysiske Medd.*, v. 25, no. 3, pp. 3-74, 1948.

- TER HAAR, D., and WERGELAND, H., On the temperature of the Earth's crust, Kgl. Norske Vidensk. Sels. Forhandlinger, v. 20, no. 14, pp. 52-54, 1948.
- URRY, W. D., Significance of radioactivity in geophysics - thermal history of the Earth, Trans. Amer. Geophys. Union, v. 30, pp. 171-180, 1949.
- VON WEIZSÄCHER, C. F., Über die Entstehung des Planetensystems, Zs. Astroph., v. 22, no. 5, pp. 319-355, 1943.
- ZEMANSKY, M. W., Heat and thermodynamics, McGraw-Hill, 2nd ed., 390 pp., 1943.

Cruft Laboratory,
Harvard University,
Cambridge, Massachusetts

(Communicated manuscript received July 8, 1949; open for formal discussion until July 1, 1950.)

AN OCCURRENCE OF SALINE GROUND WATER ON GUADALCANAL

R. C. Baker

(Published by the permission of the Director, United States Geological Survey)

Abstract--Guadalcanal Island is largely mountainous, but on the north side there is a coastal plain about 40 mi long which averages eight miles in width and stands a about 15 ft above sea level. This plain is composed of the coalesced deltas of several large rivers. Most of the military installations of World War II were located on this plain near its western end. Wells drilled for water supply disclosed a body of saline ground water between the Lunga and Nalimbu Rivers. The saline water probably is ocean water that was incorporated into the sediments as the coastal plain was built. The location and shape of the body of salt water appears to be controlled largely by the permeability of the material.

General--Guadalcanal, one of the southernmost islands of the Solomon group, is located at about 10°S and 160°E. It is about 85 mi long and 30 mi wide, the long axis extending approximately east-west. The interior of the island consists of jungle-covered mountains which rise to an altitude of over 8000 ft. This mountainous backbone is nearer to the south side of the island than the north, with the result that the longest and largest rivers flow northward. The streams on the north side have formed deltas which have coalesced to form a flat coastal plain about 40 mi long which averages eight miles in width (see Fig. 1). The coastal plain may have been uplifted slightly relative to sea level as its surface is at an elevation of about 15 ft. To the west the surface of the plain passes, without any perceptible change in altitude, onto a bench which, in part, appears to be an uplifted reef. Originally, the coastal plain was partly covered with tall grass and partly with jungle, particularly

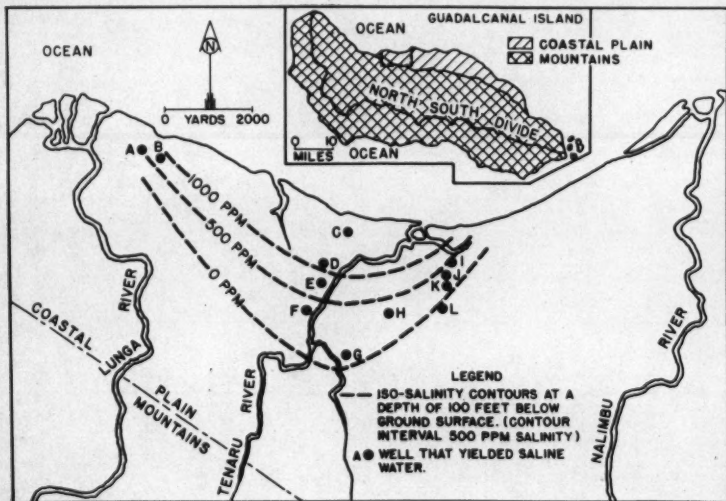


Fig. 1--North side of Guadalcanal as shown on inset

on the natural levees of the streams. Much of the plain is now covered by coconut plantations. The surface of the plain is generally flat and poorly drained. During the rainy seasons it tends to be marshy and there are areas of standing water.

Most of the military installations of World War II on Guadalcanal were located near the western end of the coastal plain. Numerous wells for water supply were put down in this area.

The material underlying the coastal plain ranges from clay to medium-coarse gravel, generally intermixed, the fine material predominating. Thick layers of clay are common. Generally, it was not possible to correlate strata from one well to the next; however, a zone of permeable sand occurs at a depth of 100 to 130 ft in several wells. Yellow clay frequently occurs at 175 to 180 ft (about 160 ft below sea level), and drillers often reported hard drilling at this depth. Grass and roots were found in two wells at about 178 ft. The maximum depth reached by any of the wells was about 500 ft, and no well reached the underlying basement rock. A layer of sand, exposed in the bank and bed of the Tenaru River near well E, dips northward toward the ocean at a rate of about one foot in 15 ft.

The yield of few wells exceeded 100 gal/min. The water is under artesian pressure, rising about to the land surface, which is about 15 ft above sea level. Water flowed from well J during rainy periods. Some wells, however, failed to penetrate any permeable material and were abandoned.

Occurrence of saline water.--Several wells located between the Lunga and Nalimbu Rivers yielded salt water. The location of these wells is shown on Figure 1, and the information relative to salt water is given in Table 1. Some of the salinity figures are only approximate. When studied to help in the location of new wells, these data gave the outline of a body of salt water occurring between the Lunga and Nalimbu Rivers. The upper surface of the body of saline water is about at sea level near the coast but dips downward going inland to the south. Isosalinity contours, showing the body of salt water, are given in Figure 1. These contours fit the known data reasonably well.

Table 1.--Depth of well, depth to top and bottom of permeable zone, and salinity of water for specified wells located between Lunga and Nalimbu Rivers, Guadalcanal Island

Well	Depth of well	Depth to top ^a and bottom of permeable zone	Salinity
	ft	ft	ppm
A	190	150	Salt water
B	500	115-140	1000
		290-310	3700
C	15±	15±	Brackish
D	120	105-120	1320
E	400	105-120	Brackish
		275-290	Brackish
		370-385	Brackish
		225-235	1600
F	240	About 130	Brackish
G	...	175-205	Brackish
H	210	365-395	Salt water
I	395	126	330
J	...	105-110	200
K	360	310-320	3600
L	260	About 260	2140

^aTop where only one figure is given

In wells B and K salinity determinations had been made at two depths, and in each the salinity increased about 1600 ppm for each 100 ft in depth. When well L was drilled it was hoped that a satisfactory yield could be obtained at about 100 to 130 ft. Permeable material, however, was not found at this depth, so drilling was continued. A satisfactory quantity of water was found at 260 ft. On the basis of the salinity data it was estimated that the water from a depth of 260 ft in well L would contain about 2400 ppm of dissolved solids. A reliable analysis showed the salinity to be 2140 ppm.

According to the basic principles that govern the occurrence of fresh water and salt water in a sand, the fresh water-salt water contact should be 40 ft below sea level for every foot the ground-

water level is above sea level. The ground-water level in the coastal plain on Guadalcanal is about 15 ft above sea level; therefore, the fresh water-salt water contact should be about 600 ft below sea level. In the plain between the Lunga and Nalimbu Rivers the upper surface of the salt water stands about at sea level near the coast. This indicates that the fresh water-salt water contact has not reached a position of equilibrium.

The origin of the body of salt water presents an interesting problem. Intrusion of ocean water into the deltaic material would be possible only if the coastal plain stood at least slightly below sea level for a considerable length of time. There is no evidence that the coastal plain has been submerged recently; instead, the most recent event may have been an uplift of a few feet relative to sea level.

Ocean water apparently was incorporated in the coastal plain as the material was deposited. The ground-water level in the plain probably has always been above sea level, and the fresh water has tended to flush the salt water out. Under this condition salt water could be incorporated into the sediments only where the plain was built out and trapped ocean water faster than ground water could move through it and flush out the salt water. The most important factor controlling the location and shape of the body of saline water appears to be the permeability of the material. The material deposited in the deltas at the mouths of the larger streams is coarser and more permeable than that deposited in the interstream areas, and the ground water at the mouths of the Lunga and Nalimbu Rivers is comparatively fresh.

References

- BADON GHYBEN, W., Nota in Verband met de voorgenomen put boring nabij Amsterdam, K. Inst. Ing. Tijdschr., 1888-1889, The Hague, p. 21, 1889.
HERZBERG, BAURAT, Die Wasserversorgung einiger Nordseebäder, J. Gasbeleuchtung und Wasserversorgung, v. 44, Munich, 1901.

Ground-water Division,
United States Geological Survey,
Little Rock, Arkansas

(Manuscript received March 4, 1949; presented at the Thirtieth Annual Meeting, Washington, D. C., April 20, 1949; open for formal discussion until July 1, 1950.)

THE ROLE OF THE ATMOSPHERE IN THE HYDROLOGIC CYCLE

George S. Benton, Robert T. Blackburn, and Vernon O. Snead

Abstract--Present day understanding of the hydrologic cycle is limited by the fact that little data have been compiled concerning mass movements of water in the atmosphere. As a result, relationships between precipitation, evapotranspiration, and runoff have been obscured. The role of the atmosphere in the hydrologic cycle is discussed, and the relationship of the hydrologic cycle to the air mass cycle is clarified. Taking the Mississippi Watershed as an example, quantitative estimates are prepared of the percentage of precipitation occurring from, and of evapotranspiration occurring into, maritime and continental air masses. These estimates are based upon quantitative studies for selected stations within the watershed. Pilot balloon and radiosonde data are utilized to determine the total flux of moisture in maritime and in continental air into the Mississippi Watershed. From these data a complete balance of the hydrologic cycle for the Mississippi Watershed is prepared. The results of this investigation are then used in analyzing the various phases of the hydrologic cycle. It is shown that only a small percentage of the maritime moisture advected over the continents is ever precipitated; that in spite of this fact most precipitation occurs from maritime air and is derived directly from oceanic sources; and that the modification of the evapotranspiration regime even over a widespread area can have comparatively little direct effect on the average quantity of precipitation recorded over that or neighboring regions.

Introduction--There are still significant gaps in our knowledge of the hydrologic cycle. In particular, very little data have been compiled concerning the role of the atmosphere in the hydrologic cycle. With few exceptions, meteorologists have not concerned themselves with this problem, and as a result there have been only a limited number of studies of large scale atmospheric movements of water. For example, data do not exist which will show the mass of water carried over the North American continent from oceanic regions, or returned from this continent over the oceans.

As late as 1935, the lack of knowledge of large scale atmospheric movements of water could be directly attributed to the inadequate number of meteorological stations taking regular measurements of the upper atmosphere. However, there are now over 50 stations in the United States and over 100 stations in North America which take radio soundings twice a day of the physical state of the upper atmosphere, including temperature, pressure, and moisture content at all elevations from the surface of the Earth up to great heights. Winds aloft are determined four times daily by over 100 stations in the United States alone by visually following free balloons with theodolites, and to this must be added a growing number of wind observations obtained by use of radar and radio direction finding techniques. When clouds prevent visual observations of pilot balloons, and if radar or radio direction finding observations are lacking, winds aloft can be estimated indirectly by using weather charts of the upper atmosphere obtained from the radio soundings.

In the last decade a large quantity of upper air data have been accumulated. This source of information is almost untouched as far as hydrometeorological studies of large scale moisture movements in the atmosphere are concerned. Before we can feel that the hydrologic cycle is fully understood, it will be necessary to compile and analyze these data. It must be remembered that flow of water across the boundaries of a watershed through the atmosphere is just as much a part of the hydrologic balance of that watershed as flow of water out of the area through river channels or by subsurface seepage.

During the last century, the lack of quantitative data and the lack of a carefully formulated qualitative presentation of the role of the atmosphere in the hydrologic cycle led to the development of significant misconceptions concerning the nature of the cycle. Hydrologists maintained that the greater part of the water which was precipitated over the continents had as its direct source the moisture evaporated from the continents. This view of the hydrologic cycle minimized the flux of water in the atmosphere to and from the oceans and essentially restricted such flow to the replenishment of water lost by the continents as runoff. This concept of a land-derived source of precipitation was not seriously questioned until recent years and is firmly established in the literature. Thus, according to the NATIONAL RESOURCES BOARD [1934]: "A considerable portion of the precipitation over any region is derived from local evaporation from that region. Only that part of the

precipitation reflected as runoff in streams of the region draining into the ocean is derived from ocean sources." Or, to take another example, HORTON [1943] wrote that "little or no vapor of truly oceanic origin may ever reach small tributary areas at the headwaters of large rivers."

The acceptance of this point of view had numerous consequences. Proposals were advanced for increasing precipitation over an area by increasing evaporation and transpiration at the expense of runoff [JENSEN, 1935]. This would be an important and useful technique if the basic assumption, on which the proposal was founded, were true. HUMPHREYS [1937], McNISH [1936], and IVES [1936] suggested the land source of precipitation as an explanation of the observed tendency of rainy days to follow rainy days, and dry days to follow dry days. For according to this view, increased precipitation will naturally follow increased evaporation, and the processes of precipitation, evaporation, and re-precipitation would then become a "chain reaction" which would continue until surface runoff would deplete the supply of available water.

The theory that precipitation is largely land-derived seems to be based on two misconceptions concerning the character of the atmosphere: (1) that increasing the amount of water vapor over an area necessarily causes an increase in precipitation over that area; and (2) that the mobility of the atmosphere is not great. The first assumption was shown to be false by HOLZMAN [1937], who pointed out that vertical motions in the atmosphere are necessary to produce important amounts of precipitation, and that vertical motions are caused by phenomena entirely separate from the factors influencing rate of evapotranspiration. However, the incorrectness of the second assumption has not been sufficiently emphasized. The atmosphere is in continuous motion. Tremendous quantities of water vapor move across the continents from the oceans, and the amount of moisture added by evapotranspiration is small. Furthermore, moisture added to the atmosphere by evaporation and transpiration rapidly moves great distances from its source. It is true that some of this moisture may be reprecipitated, but generally the area of reprecipitation will be hundreds or even thousands of miles distant, and, as will be shown, the percentage of evaporated moisture which can be reprecipitated is small.

In an excellent paper, HOLZMAN [1937] attacked the theory of land-derived precipitation and advanced the more nearly correct theory that essentially all precipitation is derived from oceanic water vapor. Holzman pointed out the relationship between the air mass cycle and the hydrologic cycle. He maintained that precipitation occurs from maritime air and evaporation occurs into continental air, and that since the air masses are distinct there can therefore be no important physical connection between the processes of evapotranspiration and precipitation. Unfortunately, Holzman was unable to advance conclusive proof for these statements. Although he clearly demonstrated that maritime air loses a portion of its water content over the land, he did not show that essentially all precipitation occurs from maritime air masses. Similarly, although he demonstrated that continental air gains in water content by evapotranspiration, he did not prove that essentially all evaporation occurs into continental air masses. Indeed, the latter statement is not true, as will be obvious from a consideration of the tremendous rates of evapotranspiration into maritime tropical air in the southeastern United States during the summer months.

Although the theory of an oceanic source for precipitation has become more widely accepted in recent years, the lack of adequate proof of this theory has prevented many hydrologists from rejecting the older hypothesis. Some attempts have been made to defend the theory of land-derived precipitation. Notably, HORTON [1943] studied the chlorine content of rainfall and runoff in the United States. He observed that the amount of chlorine in the runoff decreases rapidly from the coast inland and concluded that only the periphery of the United States obtains its precipitation from oceanic water vapor. Horton estimated that 95 per cent of the precipitation in the United States has land evapotranspiration as its direct source. However, Horton's study was based on the erroneous assumptions that: (1) all condensation nuclei are sea salt; and (2) all of the chlorine found in precipitation comes from condensation nuclei. SIMPSON [1941ab] has shown that hygroscopic nuclei other than sodium chloride may be of importance in condensation and precipitation; FINDESEN [1937] has shown that when there is a high chlorine content in the analyzed rainfall, the chlorine is not from condensation nuclei but rather from large salt particles which fall with the rain. Since such large salt particles cannot be carried great distances from the ocean, high chlorine content of precipitation is necessarily a characteristic only of coastal regions. Horton's conclusions are therefore unjustified.

On the basis of published studies, one can only conclude that the source of precipitation has not yet been demonstrated. The role of the atmosphere in the hydrologic cycle is still far from clear. What percentage of precipitation is land-derived and what percentage is oceanic in origin is not known. It is important that more evidence be brought forward so that these questions can be answered.

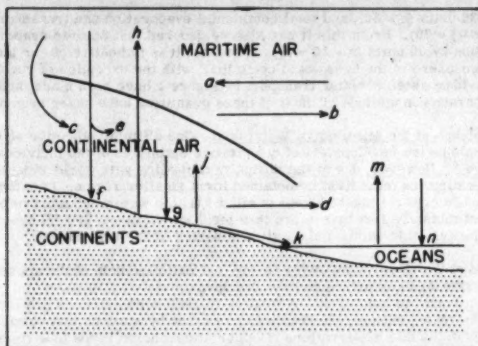


Fig. 1--The role of the atmosphere in the hydrologic cycle

The present study represents such an attempt. In addition to presenting a preliminary qualitative analysis, a quantitative study of the hydrologic balance of the Mississippi Watershed is undertaken, and the results are used to point out the actual interrelationships of runoff, precipitation, and transpiration.

A qualitative outline of the atmospheric water cycle--Diagrammatically, the hydrologic cycle and its relationship to the air mass cycle are shown in Figure 1. Here each arrow represents a flux of water in vapor, liquid, or solid form, and each letter represents an average rate of flow in mass per unit time. Maritime air movements result in a transport of tremendous quantities of water over the continents (arrow labelled a). To this amount is added water which is evaporated from the land surfaces h. The sum of these two must be balanced by loss of water either by return over the oceans b, by precipitation from the maritime air f, or by transfer of water from the maritime to continental air masses c and e. The latter transfer can be effected in several ways. Part of the maritime air remains over the continents and is modified to form continental air. The fact that the air which undergoes this transition includes a certain amount of moisture enables fresh continental air to have a certain initial moisture charge in its source region. The transfer of water from maritime to continental air represented by this process is indicated in Figure 1 by the arrow labelled c. Other ways in which continental air can gain water from maritime air are by mixing across the frontal surfaces separating the air masses and by the evaporation of precipitation falling from a maritime air mass through a continental air mass. The net transfer of water from maritime to continental air due to mixing or to evaporation of falling precipitation is shown in Figure 1 by the arrow labelled e. Considering the processes as a group, we have the relationship that over a long period of time

$$a + h = b + c + e + f \dots \dots \dots (1)$$

A similar balance may be set up for continental air. To the initial moisture charge of the continental air c is added moisture from maritime air e and moisture from evaporation and transpiration from land surfaces j. This total amount of water must be equal on the average to moisture losses due to precipitation from the continental air g and to a net transport of moisture from the continent by the continental air d. Thus, we may also write

$$c + e + j = g + d \dots \dots \dots (2)$$

In order to complete the picture of the hydrologic cycle, arrows have been entered representing runoff from the continents, and precipitation and evaporation over the oceans. For the continents, precipitation must balance runoff and evaporation, and hence

$$f + g = h + j + k \dots \dots \dots (3)$$

For the oceans, precipitation plus runoff from land areas must balance evaporation, and hence

$$k + n = m \dots \dots \dots (4)$$

On the basis of measurements of precipitation and runoff from land areas, it is possible to assign relative weights to certain of the above rates of moisture transport. Thus if total precipitation over continental areas is 100 units ($f + g = 100$), the runoff from the continents to the oceans

is approximately 30 units ($k = 30$), and total continental evaporation and transpiration will be approximately 70 units ($n + j = 70$). From this it can also be deduced that oceanic evaporation must exceed oceanic precipitation by 30 units ($n + 30 = m$). However, it is indicative of our lack of knowledge of the role of the atmosphere in the hydrologic cycle that, with the exception of runoff k , measurements of none of the individual rates of water transport in Figure 1 have been made, and even careful estimates of the comparative magnitude of most of these quantities have never been advanced.

Hydrologic balance of the Mississippi Watershed--One ultimate objective of studies of the hydrologic cycle should be the development of quantitative estimates of the individual rates of moisture transport in Figure 1. However, due to the difficulty of dealing with world wide or even continental data, preliminary estimates must first be obtained for a smaller region. In selecting a watershed for detailed study, two criteria must be kept in mind: (1) the watershed must be sufficiently large, so that estimates of moisture flux have more than local significance; and (2) observations of the upper atmosphere must be available within and on all boundaries of the watershed.

The watershed of the Mississippi River is one that satisfies both of the above criteria to best advantage. This watershed comprises an area of approximately 1,250,000 sq mi, and includes climates ranging from humid to semi-arid. A total of 18 radiosonde stations are located within the watershed, and numerous additional observations are taken by stations just outside the watershed divides. Over 35 stations take observations of upper atmospheric winds four times a day. In addition to these advantages, excellent runoff and precipitation data are available. The area is open to invasions of continental polar air, primarily from the north, and to invasions of maritime tropical air from the south. Mountain barriers to the west and the prevailing west-east circulation in mid-latitudes inhibit the movement of large quantities of moisture into the area across the western or eastern boundaries of the watershed.

In considering the hydrologic balance of a particular watershed, however, certain modifications of the general picture illustrated in Figure 1 must be introduced. These modifications arise from the fact that continental air masses may flow into the watershed from external continental areas. This influx is particularly pronounced in the case of a watershed, such as that of the Mississippi River, which is not a source region for continental air.

The hydrologic balance of the Mississippi Watershed, or of any other sub-continental area, is shown in Figure 2: Here the arrow labelled c represents the total amount of moisture carried into the area by continental air, and d still represents the total amount carried out of the area by continental air. The arrows c and d have been placed at opposite extremes of the figure purely for the sake of convenience; continental air may move into and out of the watershed across any or all boundaries. The arrows a and b represent in a similar fashion the total flux of moisture in maritime air into and out of the watershed. It is to be noted that (2) and (3) apply to the cycle illustrated in Figure 2 as well as to that in Figure 1. For sub-continental areas, however, (1) must be modified slightly to read

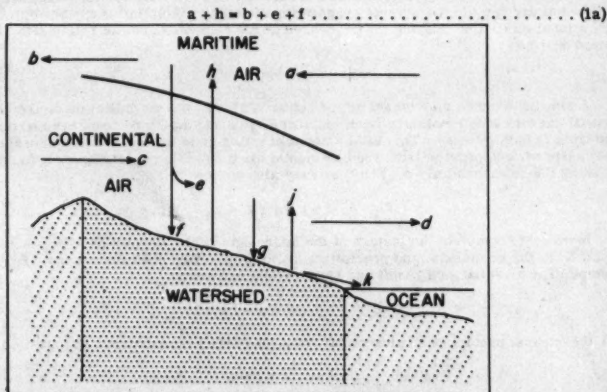


Fig. 2--The role of the atmosphere in the hydrologic cycle over a single watershed

Having determined the basic structure of the hydrologic balance of the Mississippi Watershed, our next task will be to arrive at careful estimates of the magnitude of the individual rates of moisture transport in Figure 2. Certain information is readily available. From precipitation maps of the United States it can be determined that the average annual precipitation over the Mississippi Watershed is 29.7 inches. For convenience, this rate will be arbitrarily assigned a weight of 100 units, and the individual rates of transport will thus be expressed as percentages of precipitation. On this basis stream gaging records show that runoff from the watershed k amounts to approximately 22 units (6.6 in/yr). Evapotranspiration must therefore total 78 units (23.1 in/yr).

Estimation of the individual rates of transport in Figure 2 falls naturally into four separate problems: (1) determination of the sources of precipitation according to air mass, that is, evaluation of f and g; (2) determination of the amount of natural evaporation and transpiration into continental and maritime air masses, that is, evaluation of h and j; (3) determination of the total inflow of moisture in maritime and continental air masses entering the Mississippi Watershed, that is, evaluation of a and c; and (4) estimation of the total direct interchange of moisture between maritime and continental air, that is, evaluation of e. With these evaluations completed, the remaining rates of flow (b and d, representing flux of moisture out of the watershed in maritime and continental air respectively) can be computed by use of the relationships expressed in (1a) and (2). Theoretically, it should be possible to evaluate b and d independently, and then use (1a) and (2) as a check. In practice, this is not feasible, however, since as will be shown the quantities a, b, c, and d are all large with respect to the other rates of transport. In equations (1a) and (2) the other rates therefore appear as small differences between two large quantities, and it would be necessary to determine a, b, c, and d with prohibitive accuracy in order to make use of these equations as an independent check.

The source of precipitation over the Mississippi Watershed--As is indicated above, our first task will be to determine the source of precipitation over the Mississippi Watershed according to air mass. The air masses which commonly appear over the Mississippi Watershed are: maritime tropical air, from the Gulf of Mexico; maritime polar air, from the Pacific; continental polar air, from Canada and the Arctic; and, occasionally, continental tropical air, from the southwest. There is only one reasonable method of determining the air mass from which precipitation is falling, and that is by a careful analysis of surface and upper air weather charts for the period of precipitation. This is a lengthy and difficult task.

Doubtful cases may arise as a result of either of two eventualities. First, a maritime and a continental air mass may both be present, one above the other, during the period of precipitation. In analyzing such a situation, surface and upper air observations and the reports of aircraft pilots must be consulted. Atmospheric cross-sections must be drawn to supplement standard meteorological charts. The relationships between the indicated cloud formations and the vertical air-mass distribution must be carefully weighed. If it can be concluded that clouds capable of producing the observed precipitation occur only in one air mass, then the problem is solved. If such clouds are observed in both air masses, however, no decision concerning the source of the precipitation can be advanced.

The second eventuality in which doubtful cases may arise occurs when it is impossible to determine definitely whether an air mass should be classified as maritime or continental. In the present study, difficulty in air-mass classification caused much less trouble than was anticipated. In most cases when precipitation was observed and when its source could be determined, the precipitating air mass was clearly either maritime or continental. The total amount of precipitation attributed to "doubtful" air masses was small. In such doubtful cases, however, air masses were classified according to the official charts of the United States Weather Bureau, published in Washington.

The great amount of labor involved in the careful determination of source of precipitation according to air mass makes it impractical to study in detail more than one year of record at one station within the Mississippi Watershed. Despite this limitation, one of the authors devoted several months to this phase of the investigation. It is fully recognized that such a limited sample, in both space and time, cannot yield a result which can be considered representative of average conditions over the watershed. Nevertheless, the results do make available for the first time data which can be extended by further less-detailed studies and by consideration of the meteorology of the Mississippi Watershed to arrive at a rational estimate of the comparative amount of precipitation from maritime and continental air over the watershed as a whole. It is not maintained that the figures which will be finally presented are anything more than a careful estimate, which may be subject to error but which is certainly of the correct approximate magnitude.

Owing to the very limited character of the analysis, particular care was devoted to the selection of the station to be studied. Obviously, the station must be one which takes hourly surface observations and which also takes upper air wind and radiosonde observations. If possible, the upper air wind observations should be taken by radar or radio direction finding techniques, so that direct observations of winds would be possible at all times. The station should also be one for which the necessary meteorological analyses should be neither too simple nor too severely complicated by local factors. Since only a single station could be chosen, no area sampling could be attempted and hence central location within the watershed was considered of secondary importance.

Within the Mississippi Valley, stations in the Gulf area would not be representative in that invasions of continental air would be far too infrequent. The northern areas east of the Mississippi River are characterized by an unusually high frequency of continental air at the surface and are further complicated by the modification effects of the Great Lakes on the air masses passing over them. This tends to increase the cloudiness in the lower levels and therefore tends to make meteorological analyses more difficult. The Plains areas are atypical in that total precipitation is substantially lower than the average for the watershed, and conditions are highly variable from year to year. The area which therefore seems most suitable for analysis is that east of the Mississippi River and in the vicinity of the Ohio River Valley. In this area, maritime and continental air are each frequently observed at the surface of the Earth. The precipitation is large enough to afford a reasonably satisfactory sample in one year, and variability of precipitation from year to year is lower than in any other region within the Mississippi Watershed.

Within the selected region there are several stations of the United States Weather Bureau which could have been chosen. The one finally selected was Huntington, West Virginia. The year analyzed was 1946. Huntington has a shielded Fergusson recording rain gage, for which hourly precipitation amounts were obtained. Four observations of winds aloft are made daily, and after February, 1946, observations were made by radio techniques. Two radiosonde flights are made daily. Investigation showed that for Huntington the year 1946 was fairly typical with regard to both precipitation occurrence and air mass frequency.

A total of 123 precipitation periods were examined, representing a total precipitation of 39.83 inches for the year. In 47 of these periods (total precipitation 21.10 inches) the only air mass present over the station was maritime in character; in three cases (total precipitation 1.96 inches) the only air mass was continental; in the other 73 cases (total precipitation 16.77 inches) maritime air was present above continental air. However, in 26 of these 73 cases (total precipitation 5.99 inches) analysis showed that clouds were present only in the maritime air. Thus, it could be established without question that 27.09 inches (68 per cent of the precipitation for the year) occurred from maritime air, while only 0.78 inches (about two per cent) occurred from continental air.

Further analysis enabled the determination of the source of precipitation in a number of additional cases. It was sometimes found, for example, that the clouds in the continental air were a type that were incapable of having produced the observed rainfall and which had probably formed as a result of the evaporation of precipitation falling from the maritime air mass aloft. In some other periods, the precipitating clouds were clearly in the continental air. Including cases of this sort, it was determined that approximately 32.09 inches (81 per cent of the total precipitation for the year) occurred from maritime air, and 2.89 inches (seven per cent of the total) occurred from continental air. The balance of 4.85 inches (12 per cent of the annual precipitation) was from a source which could not be determined with any degree of confidence. In most of these cases, the precipitation occurred from a diffuse frontal surface with the precipitating clouds partly in the maritime and partly in the continental air. As a result of these data, it may be indicated that of the precipitation at Huntington in 1946, probably 85-90 per cent came from maritime air and 10-15 per cent from continental air. Preliminary investigations for other years of record show that these figures are not unreasonable and can be used with some assurance as representative of conditions for Huntington over a longer period of time.

In using this information to arrive at an estimate for the Mississippi Watershed as a whole, there are many factors to be taken into account. In the states bordering the Gulf, invasions of continental polar air occur only in winter, which is a season of low precipitation. It is certain, therefore, that the percentage of precipitation from maritime air increases steadily towards the south, reaching a maximum of more than 95 per cent in the vicinity of New Orleans. Towards the north, however, the reverse will be the case. In Minnesota, for example, continental polar air is frequently observed at the surface of the Earth both in winter and summer, and the percentage of precipitation from maritime tropical or maritime polar air must be considerably lower, possibly as low as 70 per cent. A similar latitudinal variation must exist throughout the Great Plains where, however, maritime polar air will be of increasing importance as a source of precipitation.

Taking into consideration the fact that annual precipitation near the Gulf is approximately twice the annual precipitation in the northern states, it is estimated that for the Mississippi Watershed as a whole approximately 90 per cent of the total mass of precipitation comes from maritime tropical or maritime polar air and approximately ten per cent comes from continental polar or continental arctic air. The authors have arrived at this estimate carefully, after preliminary surveys of precipitation regimes at several additional stations, and feel that it is not subject to an error of more than 5 per cent. For the Mississippi Valley, therefore, we have arrived at the final estimate that precipitation from maritime air (arrow f in Figure 2) totals 90 units (26.7 in./yr) and that precipitation from continental air (arrow g in Figure 2) totals ten units (3.0 inches). Other rates of moisture flux in Figure 2 must now be evaluated.

Evapotranspiration over the Mississippi Watershed--The next problem is the determination of the amount of evapotranspiration into maritime and continental air which takes place within the Mississippi Watershed. This is a problem which cannot be attacked as directly as the determination of precipitation source. No accurate method exists for the day by day measurement of natural evapotranspiration at a station, and since maritime and continental air masses in general appear one after the other in rapid succession over an area, there is no obvious method of separating the evapotranspiration into one air mass from the evapotranspiration into another.

It has been possible, nevertheless, to attack this problem indirectly from an examination of three sets of data: (1) Pan evaporation records at Class A Weather Bureau evaporation stations; (2) precipitation records at these same stations; and (3) air mass occurrence tabulations. For each station and for each season, pan evaporation data were first used, in conjunction with air-mass classifications, to determine the average daily pan evaporation into maritime and continental air, respectively. These data gave an indication of what the comparative magnitude of the average daily natural evapotranspiration into maritime and continental air would be, provided unlimited moisture were available. In general, of course, this provision would not hold true. However, the basic assumption was made that if the ratio of the average daily pan evaporation in maritime air to the average daily pan evaporation in continental air is A/B the ratio of average daily natural evapotranspiration into maritime air to the average daily evapotranspiration into continental air would also be A/B, provided that the water supply available when maritime air was present was equivalent to that available when continental air was present over the station. It is recognized that this assumption is probably not exact; nevertheless, it is an adequate working hypothesis.

To determine whether moisture availabilities were equivalent when maritime and continental air were over a station, it was necessary to compare precipitation and air-mass occurrence data. In several cases it was found that the moisture available to the two types of air masses was not entirely equivalent, that is, that periods of precipitation tended to precede, on the average, periods of occurrence of maritime (or continental) air. In this event, a subjective correction of the ratio A/B was indicated. In no case, however, was moisture availability so different that a considerable correction was warranted. This is particularly true since in most areas a considerable portion of the natural water loss is in the form of transpiration, which proceeds at a rate largely independent of soil moisture content except during periods of drought [HORTON, 1943].

Once the ratio of the average daily natural evapotranspiration into maritime air to the average into continental air had been estimated for each season, air-mass frequency tabulations were used to determine the ratio of the seasonal evapotranspiration totals into each air mass. For each station these seasonal ratios were then used, in conjunction with known annual evapotranspiration totals for the year and carefully prepared estimates for the seasons, to determine quantitatively the annual evapotranspiration into maritime and into continental air. Finally, data for the various stations were combined geographically to give one total for the Mississippi Watershed. Although these final figures are the end product of computations involving several assumptions and approximations, it is believed by the authors that the resulting estimates are close to the true figures. Certainly the error involved is not large enough to invalidate the use of our estimates in reconstructing the approximate hydrologic balance of the Watershed.

In the analysis, five Class A Weather Bureau evaporation stations were considered. These are, Pleasantville, New Jersey; Dayton, Ohio; Lock A, Tennessee; Austin, Texas; and Bridgeport, Nebraska. Actually, two of these stations are outside the Mississippi Watershed, since initially this phase of the investigation was undertaken to determine comparative evaporation into maritime and continental air for the entire eastern half of the United States. Evaporation pan records for each of these stations were analyzed for the five years from 1942-1946, inclusive. Each year was divided into two seasons: summer (May through October), and winter (November through April). For each station and each season, pan evaporation into maritime and continental air was tabulated. On days when both maritime

and continental air were present over a station, the pan evaporation for that day was recorded as "undetermined." It was possible to obtain complete records for only two of the five stations during the winter season. However, during the winter season Lakehurst, New Jersey, was used to replace Pleasantville.

The result of these tabulations are shown in Table 1. Inspection of this table reveals that in the presence of an unlimited supply of water, the ratio of average daily evaporation into continental air to average daily evaporation into maritime air is amazingly close to unity. In seven of the eight station seasons, this ratio is between 0.75 and 1.25. This is surprising, in view of the complexity of the factors involved. It may be that, on the average, lower dew points in the continental air (which would tend to increase evaporation rates) are counterbalanced by more stable vertical temperature distributions (which would tend to decrease evaporation rates). However, it must be pointed out that despite the similarity between average daily evaporation rates into continental and maritime air, there is an almost uniform tendency for pan evaporation rates to be slightly higher in the latter type of air mass. The over-all ratio is about 4/5.

Table 1--Pan evaporation data by air mass

Station	Pan evaporation by air mass			Frequency of each air mass			Average daily pan evaporation		
	M ^a	C ^b	U ^c	M ^a	C ^b	U ^c	M ^a	C ^b	U ^c
	in	in	in	day	day	day	in	in	in
Summer									
Pleasantville	60.1	70.6	22.5	370	407	129	0.16	0.17	0.17
Dayton	61.2	75.7	17.1	314	480	121	0.19	0.16	0.14
Lock A	85.4	53.6	19.7	455	341	120	0.19	0.16	0.16
Austin	184.3	29.4	25.2	668	144	108	0.28	0.20	0.23
Bridgeport	48.9	99.8	30.2	216	551	136	0.23	0.18	0.22
Winter^d									
Lock A	19.4	66.5	14.1	159	623	124	0.12	0.11	0.11
Austin	37.2	45.5	17.3	299	465	151	0.12	0.10	0.11
Lakehurst	20.0	66.2	13.6	84	367	72	0.24	0.18	0.19

^aM, maritime; ^bC, continental; ^cU, undetermined; ^ddata for Pleasantville, Dayton, and Bridgeport were incomplete because of freezing conditions and could not be used.

In accordance with the outlined procedure, tabulations were then made for each of the ten stations seasons showing the relationship of precipitation and subsequent air mass occurrence. The result of this study showed that for Pleasantville and Dayton, there is no important correlation between summer precipitation and subsequent air mass occurrence. Lock A and Austin show a slight tendency for higher precipitation preceding the occurrence of continental air, while Bridgeport shows a tendency for higher precipitation preceding maritime air. These results are reasonable from a meteorological point of view, since south of the mean position of the polar front summer precipitation is largely convective and would be most intense in the southerly flow of air ahead of a strong polar trough with its associated subsequent influx of continental air. On the other hand, in Nebraska thunderstorms are largely nocturnal in character and frequently occur on those days when strong northward movement of maritime air results in a stagnant or slowly moving polar front just north of the observing station [MEANS, 1944]. In the winter, all of the stations except Pleasantville, New Jersey, show a tendency for higher precipitation preceding the occurrence of continental air. This probably reflects the importance over the Mississippi Watershed of winter cold front precipitation as well as precipitation from stagnant or slowly moving warm fronts.

The above data have enabled us to make an estimate of the relative daily natural evapotranspiration into maritime and continental air. The estimates used are shown in Table 2. Table 3 presents for each station the resulting seasonal and annual evapotranspiration according to air mass. In arriving at these results, it has been necessary not only to take into consideration relative air-mass frequencies, summer and winter, but also to estimate the percentage of evapotranspiration occurring during the warm and cold seasons at each station. This has been done after examining seasonal pan evaporation and precipitation records. Our estimates agree reasonably well with the suggestion of HORTON [1943] that 85 per cent or more of summer precipitation and 30-35 per cent of winter precipitation is returned to the atmosphere.

Table 2--Ratio of rate of evapotranspiration into maritime and continental air

Station	Summer	Winter
Pleasantville	1 : 1	3 : 2
Dayton	5 : 4	1 : 1
Lock A	1 : 1	4 : 5
Austin	1 : 1	2 : 3
Bridgeport	3 : 2	2 : 3

It is to be noted that the percentage of annual evapotranspiration occurring into maritime air increases steadily towards the south. This fact is brought out clearly in Figure 3, which has been prepared from the data in Table 3. By comparing Figure 3 with a map of annual evapotranspiration, Figures 4 and 5 have been drawn. Evapotranspiration into continental air is shown to be reasonably constant over the eastern United States, while evapotranspiration into maritime air occurs predominantly in the southern states.

Table 3--Evapotranspiration by air mass

Station	Summer			Winter			Annual		
	M ^a	C ^b	T ^c	M ^a	C ^b	T ^c	M ^a	C ^b	T ^c
Pleasantville	8.1	8.8	16.9	1.2	4.7	5.9	9.3	13.5	22.8
Dayton	7.6	9.3	16.9	0.5	5.5	6.0	8.1	14.8	22.9
Lock A	11.5	8.4	19.9	1.6	7.7	9.3	13.1	16.1	29.2
Austin	13.9	3.1	17.0	2.8	6.4	9.2	16.7	9.5	26.2
Bridgeport	3.8	6.6	10.4	0.2	2.4	2.6	4.0	9.0	13.0

^aM, maritime; ^bC, continental; ^cT, total

By planimetering Figures 4 and 5 for areas within the Mississippi Watershed, it has been determined that of the 78 units (23.1 inches) of evapotranspiration within the Watershed, approximately 35 units (10.4 inches) occur into maritime air and approximately 43 units (12.7 inches) into continental air. It might be noted that these figures are fairly stable for any reasonable estimate of comparative seasonal evapotranspiration at the key stations. The authors are therefore confident that the annual evapotranspiration data by air mass are approximately correct.

Moisture transport into the Mississippi Watershed.--In our analysis of the hydrologic cycle of the Mississippi Watershed the major remaining problem is to evaluate the flux of water in vapor form. This problem is, however, comparatively simple of solution. Radio soundings and pilot

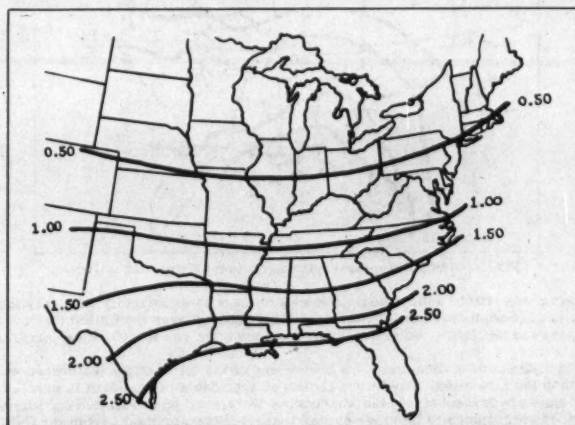


Fig. 3--The ratio of annual evapotranspiration into maritime air to evapotranspiration into continental air over the eastern United States

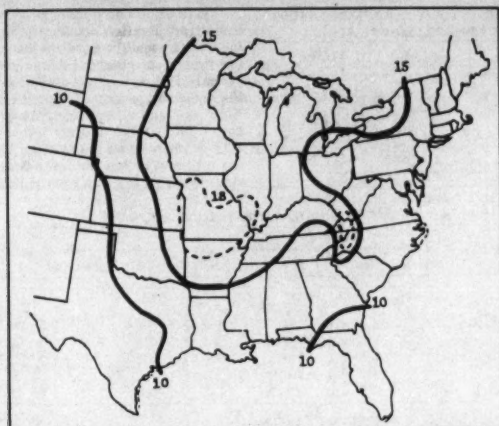


Fig. 4--Annual evapotranspiration into continental air, in inches

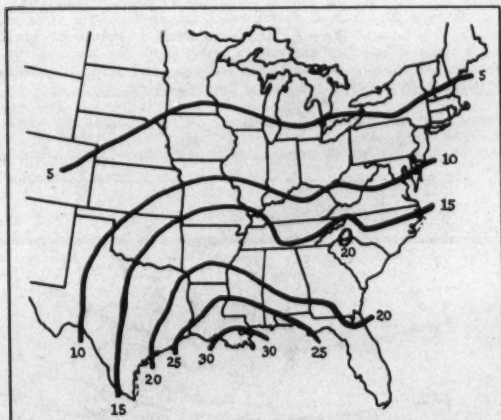


Fig. 5--Annual evapotranspiration into maritime air in inches

balloon observations enable meteorologists to determine with satisfactory accuracy the density of water vapor and the wind speed and direction at all elevations over the United States. By lengthy but straightforward tabulation, water transport in vapor form can therefore be computed.

Fourteen radiosonde stations near the boundaries of the Mississippi Watershed were selected as key points in the tabulation. Days were chosen at approximately uniform intervals from the years 1946-1948. Moisture transport into the Mississippi Watershed was tabulated for summer and winter, and was divided geographically into four categories: (1) Flow northward from the Gulf of Mexico; (2) flow southward from Canada; (3) flow eastward from west of the Rocky Mountains; and (4) flow from Mexico and the Southwest. The statistical sample for each season and each geographic sector

was extended until the standard error of the mean daily transport was at least less than 20 per cent (usually less than 10-15 per cent) of the mean value. Further extension of the sample was considered unnecessary; water transport into the Mississippi Watershed in vapor form was obviously of a different order of magnitude from precipitation, evapotranspiration, and the other phases of the hydrologic cycle. Determination of moisture flux to the accuracy specified was sufficient for the purposes of this study.

Results are shown in Table 4. Approximately 488 units (146 inches) of moisture enter the Mississippi Watershed yearly. Most of this moisture is in maritime air. Almost all of the 218 units (65 inches) moving north from the Gulf of Mexico is in maritime air. In addition, part of the air moving eastward across the Rocky Mountains is maritime, especially during the winter months. Also, in the summer, maritime polar air from the Pacific moves across Canada and enters the United States from the northwest, across the Canadian Border. Taking these facts into consideration, we estimate that of the 488 units, approximately 335 (100 inches) are associated with maritime air masses, and 153 units (46 inches) are associated with continental air.

Table 4--Moisture transport into the Mississippi Watershed

Boundary	Summer	Winter	Annual
	In	In	In
Gulf of Mexico	35	30	65
Southwest	6	3	9
Rocky Mountains	17	16	33
Canada	27	12	39
Totals	85	61	146

We are now in a position to complete our picture of the hydrologic cycle for the Mississippi Watershed, as soon as an estimate is obtained for the direct exchange of moisture from maritime to continental air. This last estimate is difficult to formulate. However, direct exchange of moisture will be small compared to total precipitation. This is particularly true since the principle cause of moisture exchange is evaporation from precipitation falling from one air mass through another, and we have seen that a large portion of the total precipitation actually occurs entirely within a single

air mass. However, it is certainly true that pre-warm front and post-cold front precipitation is frequent in occurrence, and that under such circumstances considerable evaporation can occur. As a tentative figure, the authors have estimated direct exchange to be ten units (2.9 inches). Although the possible error in this estimate is high, the absolute magnitude of the moisture transport involved is small, so that such an error would not affect our final analysis materially.

The hydrologic cycle of the Mississippi Watershed--By use of equations (1a) and (2) it is now possible to balance completely the hydrologic cycle for the Mississippi Watershed. The cycle is shown in Figure 6. Perhaps the most striking point in this diagram is the role of the atmosphere

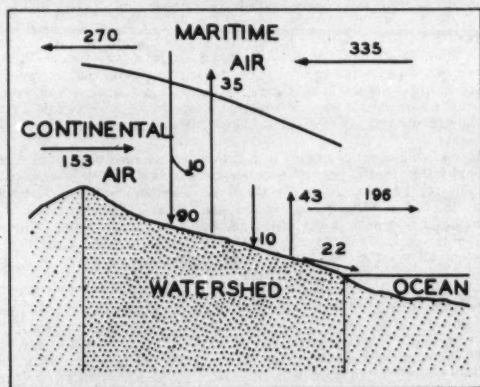


Fig. 6--The role of the atmosphere in the hydrologic cycle of the Mississippi Watershed (mean annual precipitation equals 100 units, or 29.7 inches)

in bringing tremendous quantities of moisture across the continental surfaces. Only a small fraction (about 20 per cent) of this water is ever precipitated. This serves to illustrate the extreme mobility of the atmosphere, a fact not adequately appreciated by those who emphasize the theory of land-derived precipitation.

Considering all exchange processes, maritime air masses moving over the Mississippi Watershed suffer a net loss in moisture amounting to approximately 20 per cent of their initial charge. On the other hand, continental air masses receive a net increase in moisture amounting to approximately 25 per cent of their initial charge. These data are for annual periods and include water vapor in the atmosphere to considerable elevations. In the winter, the increase in moisture content of fresh continental polar air masses moving over the Mississippi Watershed is considerably larger, especially in the surface layers.

By use of the data in Figure 6, we can now estimate to what extent precipitation has a land source. Assume for a moment that water evaporated or transpired into a maritime air mass immediately mixes with its environment by atmospheric convection. Consider a water molecule which is evaporated into a maritime air mass already containing a mass of water vapor, M . The probability that this particular molecule will be returned to Earth as precipitation is approximately P/M , where P is the mass of water subsequently precipitated from the air mass. The value of the ratio P/M for maritime air entering the watershed averages 90/335, or 0.27; for air just leaving the watershed it is zero. If we take the mean value of P/M to be 0.15, then of the 35 units of evapotranspiration 35 times 0.15 (or about five units) will be re-precipitated.

Actually, owing to the initial concentration of the evaporated moisture in the lower levels of the atmosphere, where it might be slightly more accessible for subsequent convective precipitation, this estimate may be a little low. However, in the case of maritime air, the most liberal estimate would certainly require that not more than 7-8 units (or eight or nine per cent of the precipitation) be derived directly from land sources within the Mississippi Watershed. The balance of the precipitation from maritime air must then be traced to air moving into the Watershed from external regions. In the case of the Mississippi Watershed, for which the primary source of maritime air is the Gulf of Mexico, this is almost equivalent to noting that the balance of the precipitation from maritime air has an oceanic origin.

If we apply similar reasoning to continental air, we find that of the ten units of precipitation, not more than two or three units are derived directly from land sources within the Mississippi Watershed. Of the balance of the precipitation from continental air, part will be from the initial moisture charge (that is, maritime in source) and part will be land-derived from regions external to the Watershed. It is possible that the latter may amount to an additional two to three units, since the initial moisture charge of continental air in its source region is comparatively low.

Considering both air masses we may state that probably not more than ten per cent of the total precipitation of the Mississippi Watershed is moisture having a land source within the Watershed, while at least 90 per cent is external in origin. Furthermore, probably not more than 12-14 per cent of the total annual precipitation is moisture having a land source either within or without the Watershed, while at least 86-88 per cent is oceanic in origin. The theory of a land source for a major portion of the precipitation is thus shown to be without foundation.

The implications of this fact are obvious. Since such a low proportion of total precipitation is land-derived, it must follow that an increase in evapotranspiration due to changes in land use will have a comparatively slight effect on the climate of the surrounding areas. Although precipitation will vary from year to year and century to century, the amount of precipitation will be primarily a function of such variables as the intensity of the hemispheric circulations. The percentage of precipitation returned to the oceans as runoff and the percentage returned directly to the atmosphere as evapotranspiration will be of decidedly secondary importance in determining annual precipitation. Precipitation is not, and cannot be, a "chain reaction."

Nevertheless the percentage of precipitation which is land derived may be large enough to warrant a word of caution. If as much as 12-14 per cent of the total precipitation over the Mississippi Watershed is actually land-derived, then possibly as much as 20-30 per cent of the precipitation over a local area may be traced to land sources. For example, it is possible that evapotranspiration into maritime tropical air in the southern part of the United States and evapotranspiration into continental polar air in Canada may together add importantly to precipitation in Iowa or Illinois. Whether or not this is actually the case can only be determined by further study. Nevertheless, even if true, this relationship could hardly be of significance economically. Owing to the extreme mobility of the atmosphere, the land sources for precipitation in one region are bound to be hundreds

or even thousands of miles away from that region. Increasing or decreasing precipitation even slightly by local regulation of land use is therefore out of the question.

Summary--The present study offers a qualitative appraisal of the role of the atmosphere in the hydrologic cycle and a quantitative analysis of this role for the Mississippi Watershed. It is shown that due to the air-mass cycle and the extreme mobility of the atmosphere only a small percentage of land precipitation is land derived. Nevertheless for local areas the balance is not clear. Further studies of mass movements of water vapor in the atmosphere must be made before the hydrologic cycle of small watersheds can be formulated.

References

- FINDEISEN, W., Entstehen die Kondensations Kerne an der Meeresoberfläche?, Met. Zs., v. 54, pp. 377-379, 1937.
- HOLZMAN, B., Sources for moisture for precipitation in the United States, U. S. Dept. Agric., Tech. Bulletin 589, 1937.
- HORTON, R. E., Hydrologic interrelations between lands and oceans, Trans. Amer. Geophys. Union, v. 24, pp. 753-764, 1943.
- HUMPHREYS, W. J., Weather rambles, Baltimore, 1937.
- IVES, R. L., Desert floods in the Sonoyta Valley, Amer. J. Sci., v. 32, pp. 349-360, 1936.
- JENSEN, J. C., The relation between surface evaporation from lakes and ponds to precipitation from local thunderstorms in the drought area, Bulletin Amer. Met. Soc., v. 16, pp. 142-145, 1935.
- McNISH, A. G., Statistical aspects of long range weather forecasting, Trans. Amer. Geophys. Union, v. 1, pp. 124-129, 1936.
- MEANS, L. L., The nocturnal maximum occurrence of thunderstorms in the mid-western United States, Misc. Rep 16, Dept. of Met., Univ. Chicago, 1944.
- NATIONAL RESOURCES BOARD, Report of the Water Planning Committee, pp. 253-388, 1934.
- SIMPSON, G. C., On the formation of clouds and rain, Q. J. R. Met. Soc., v. 67, pp. 99-133, 1941a.
- SIMPSON, G. C., Sea salt and condensation nuclei, Q. J. R. Met. Soc., v. 67, pp. 163-169, 1941b.

The Johns Hopkins University (G. S. B.),
Baltimore, Maryland

University of Chicago (R. T. B.),
Chicago, Illinois

Air Weather Service (V. O. S.),
U. S. Air Forces,
Chanute Field, Illinois

(Manuscript received April 7, 1949; presented at the Thirtieth Annual Meeting, Washington, D. C., April 20, 1949; open for formal discussion until July 1, 1950.)

EFFECTS OF PARTICLE SHAPE ON SETTLING VELOCITY
AT LOW REYNOLDS NUMBERS

John S. McNown and Jamil Malalaka

Abstract--Extensive theoretical and experimental studies have been conducted at the Iowa Institute of Hydraulic Research in an investigation of the effect of shape on the settling velocity of particles. A number of representative axisymmetric shapes were used in the experiments, the Reynolds numbers of the particle motion ranging from 10^{-4} to 10^{+1} . Stability of orientation was also investigated. Analytical results were obtained for the motion of ellipsoids within the Stokes range by solving Oberbeck's integral equation. The ratio of the principal-axis lengths was found to be by far the most significant of the various shape factors which have been proposed. In fact, the settling velocities of particles over a wide range of shape can be estimated within ten per cent from the theoretical results for ellipsoids.

Introduction--Simplified shape factors based on the principal-axis lengths of settling particles should be immediately applicable to such widely diversified problems as the siltng of reservoirs, sorting of abrasives, and determining the electrical charge on dust particles. In many particle analyses, the settling velocity is the sole quantity determined, the volume and diameter being assumed equal to those of a sphere which settles at the same rate. Since a change in shape, or even in orientation, can markedly alter the particle velocity, serious errors may result from such simplification of the problem. The absence of a reasonably accurate yet straightforward method of approximating shape effects has prevented, heretofore, the attainment of more satisfactory results.

The manner in which settling velocity varies with particle shape at low Reynolds numbers has been investigated both theoretically and experimentally at the Iowa Institute of Hydraulic Research. Analysis of the motion of ellipsoids, representing an extension of Stokes' solution for spheres, has disclosed a wealth of information on the effect of primary shape factors. In addition, fall velocities of ellipsoidal and other regularly shaped particles have been determined experimentally, and the ratios of the axis lengths have proved to be both significant and practicable shape factors.

Analysis of ellipsoidal-particle motion--Valuable information on shape effects can be obtained from a theoretical analysis of the motion of ellipsoids through viscous fluids, since the ellipsoidal form is infinitely variable from disk-like through spherical to rod-like shapes. Completing the solution of the integral equations obtained by Oberbeck [LAMB, 1945, pp. 604-605] provides data concerning particle motion for which inertial effects can be neglected. The solution for the case in which two of the ellipsoidal axes are equal is obtainable by ordinary calculus, but the general solution involves elliptic integrals.

For investigations of the motion of small particles the well known Stokes law is often used. Stokes showed that the resistance F to the motion of a spherical particle through a viscous fluid will be proportional to the product of the viscosity μ of the fluid and the velocity V and diameter D of the particle, provided that the fluid medium is infinite in extent and that the inertial forces are negligible compared to the viscous forces. If either of these conditions is not satisfied, the constant of proportionality will change. Moreover, if the shape of the particle is not spherical, the single dimension D will no longer be sufficient to describe the particle geometry. An equivalent diameter D' has been defined as the diameter of a spherical particle with the same settling velocity as a given non-spherical particle, in order that the Stokes law may be used for particles of any shape. However, such a procedure tends to obscure shape effects rather than explain them, since often neither the shape nor the size of a particle is determined. An alternative dimension, which is directly related to the particle characteristics rather than to those of its motion, is the nominal diameter, which is that of a sphere of the same volume. Throughout the ensuing discussion, although shape must also be described in some manner, the symbol D will denote the nominal diameter.

A more general form of the Stokes equation can be written if a proportionality factor K is introduced as follows

$$F = (3\pi\mu VD)K \dots \dots \dots (1)$$

If the Reynolds number of the particle motion ($R = \rho VD/\mu$, in which ρ is the mass density of the fluid) is sufficiently small and if the container or the particle spacing is sufficiently large, K is then a function of particle shape alone. An interpretation of the significance of K is indicated by the relationship

$$K = V_s/V \dots \dots \dots (2)$$

which may be obtained from (1), V_s representing the velocity of a sphere with diameter equal to the nominal diameter of the particle.

For ellipsoidal particles moving in the direction of one of the principal axes, the following expression for K can be derived from the final result of Oberbeck

$$K = 16/3D(\alpha + \beta) \dots \dots \dots (3)$$

in which

$$\alpha = \int_0^\infty \frac{1}{[1/\sqrt{(a^2 + \xi^2)(b^2 + \xi^2)(c^2 + \xi^2)}]} d\xi \dots \dots \dots (4)$$

and

$$\beta = a^2 \int_0^\infty \frac{1}{[1/(a^2 + \xi^2)\sqrt{(a^2 + \xi^2)(b^2 + \xi^2)(c^2 + \xi^2)}]} d\xi \dots \dots \dots (5)$$

The arbitrary variable ξ disappears if the integrations are performed and the limits are substituted in the resulting expressions; a , b , and c are the semi-axes of the ellipsoid, the direction of motion being parallel to the a -axis. The nominal diameter may be evaluated from the equation

$$D = 2(abc)^{1/3} \dots \dots \dots (6)$$

From examination of (3) to (5) it can be concluded that α is purely a shape factor, since it is independent of orientation, while the magnitude of β is also dependent upon which axis coincides with the direction of motion. The fact that b and c are evidently interchangeable in (5) leads to a reduction in the number of possible forms for evaluating the integral.

The various final expressions for α and β , which depend upon the relative magnitudes of a , b , and c , are summarized in Table 1. For conditions 2 to 5, items 114, 119, 123, and 681 of PEIRCE [1929] were used; for conditions 6 to 8, no solutions for the elliptic-integral forms were found, although tabulated values of the two basic types of elliptic integrals are included in many sets of mathematical tables.

In Figure 1 is shown the variation of K with the length ratios $a/\sqrt{bc}$ and b/c as determined from Table 1. The first ratio, plotted as the abscissa scale, is the semi-axis in the direction of motion divided by the radius of a circle with an area equal to the projection of the ellipsoid normal to the direction of motion. Since the projected area depends on both b and c , neither alone is as significant as the product of the two. For the lowermost curve the projected area is a circle; for the uppermost, an elongated ellipse. Since b and c are interchangeable, b is always taken to be the larger. That the orientation is on the one hand significant and on the other hand is taken into account in Figure 1 can be demonstrated by considering the indicated results for a particle with axes in the ratios 1:2:8. If the motion is in the direction of (1) the shortest axis, $a/\sqrt{bc} = 1/4$, $b/c = 4$, and $K = 1.56$; (2) the intermediate axis, $a/\sqrt{bc} = 1/\sqrt{2}$, $b/c = 8$, and $K = 1.41$; and (3) the longest axis, $a/\sqrt{bc} = 4\sqrt{2}$, $b/c = 2$, and $K = 1.10$. In this instance the maximum resistance is more than 40 per cent greater than the minimum even though the particle shape is the same in each case.

Somewhat surprising is the occurrence of a geometric range for which K is less than unity. Although the well streamlined shape is known to lead to relatively low resistance at high Reynolds numbers, the idea is prevalent that the spherical shape is the most effective for low Reynolds numbers. Streamlining for the purpose of reducing separation is entirely out of place for viscous motion, but some arrangement of the particle mass surely exists for which the resistance is a minimum. For the ellipsoidal shape, the circular cross section and an ellipsoidal profile somewhat elongated in the direction of motion lead to resistances for a given volume which are several per cent less than that for the sphere. The minimum value of K , which is 0.955, occurs for $a/\sqrt{bc}$ slightly less than two. It is entirely possible that other geometrical shapes would lead to even smaller values.

From an examination of Figure 1 it is apparent that variation in geometry has only a small effect in the region of minimum resistance. A change of a factor of two from the ratios for minimum

Table 1--Values of α and β

1. $a=b=c$:	$\alpha = 2/a$ $\beta = 2/3a$
2. $a=b>c$:	$\alpha = \frac{2}{\sqrt{a^2-c^2}} \tanh^{-1} \frac{\sqrt{a^2-c^2}}{c}$ $\beta = \frac{a^2}{(a^2-c^2)^{3/2}} \left(\tanh^{-1} \frac{\sqrt{a^2-c^2}}{c} - \frac{c\sqrt{a^2-c^2}}{a^2} \right)$
3. $a=c<b$:	$\alpha = \frac{2}{\sqrt{b^2-a^2}} \tanh^{-1} \frac{\sqrt{b^2-a^2}}{b}$ $\beta = \frac{a^2}{(b^2-a^2)^{3/2}} \left(\frac{b\sqrt{b^2-a^2}}{a^2} - \tanh^{-1} \frac{\sqrt{b^2-a^2}}{b} \right)$
4. $a>b=c$:	$\alpha = \frac{2}{\sqrt{a^2-c^2}} \tanh^{-1} \frac{\sqrt{a^2-c^2}}{a}$ $\beta = \frac{2a^2}{(a^2-c^2)^{3/2}} \left(\tanh^{-1} \frac{\sqrt{a^2-c^2}}{a} - \frac{\sqrt{a^2-c^2}}{a} \right)$
5. $a<b=c$:	$\alpha = \frac{2}{\sqrt{c^2-a^2}} \tanh^{-1} \frac{\sqrt{c^2-a^2}}{a}$ $\beta = \frac{2a^2}{(c^2-a^2)^{3/2}} \left(\frac{\sqrt{c^2-a^2}}{a} - \tanh^{-1} \frac{\sqrt{c^2-a^2}}{a} \right)$
6. $a>b>c$:	$\alpha = \frac{2F(\varphi_1, k_1)}{\sqrt{a^2-c^2}}$ $\beta = \frac{2a^2[F(\varphi_1, k_1) - E(\varphi_1, k_1)]}{(a^2-b^2)\sqrt{a^2-c^2}}$ $\varphi_1 = \sin^{-1} \frac{\sqrt{a^2-c^2}}{a}, \quad k_1 = \frac{\sqrt{a^2-b^2}}{\sqrt{a^2-c^2}}$
7. $b>c>a$:	$\alpha = \frac{2F(\varphi_2, k_2)}{\sqrt{b^2-a^2}}$ $\beta = \frac{2a^2 \left[\frac{c}{ab} - \frac{E(\varphi_2, k_2)}{\sqrt{b^2-a^2}} \right]}{c^2-a^2}$ $\varphi_2 = \sin^{-1} \frac{\sqrt{b^2-a^2}}{b}, \quad k_2 = \sqrt{\frac{b^2-c^2}{b^2-a^2}}$
8. $b>a>c$:	$\alpha = \frac{2F(\varphi_3, k_3)}{\sqrt{b^2-c^2}}$ $\beta = \frac{2a^2 \left[\frac{k_3}{\sqrt{b^2-a^2}} E(\varphi_3, k_3) - \frac{k_3-k_3}{\sqrt{b^2-a^2}} F(\varphi_3, k_3) - \frac{c}{ab} \right]}{a^2-c^2}$ $\varphi_3 = \sin^{-1} \frac{\sqrt{b^2-c^2}}{b}, \quad k_3 = 1/k_2$

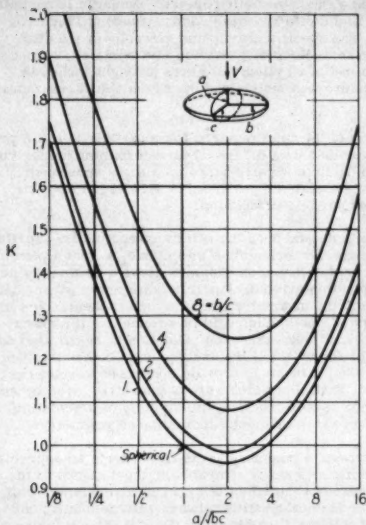


Fig. 1--Coefficient of resistance for ellipsoids as a function of simplified shape parameters

The specific gravity of the particles was determined by weighing a large sample of the stock from which the particles were machined, the volume of the sample being accurately determined. Each

resistance increases K less than eight per cent. However, not only is the resistance much greater for particles with markedly unequal axes than for the sphere of equal volume, but it is also subject to marked change with variations in proportion.

Experimental Investigations--Because the effects of other shape factors than the principal-axis ratios cannot be evaluated analytically, fall velocities for particles of various simply defined shapes must be determined experimentally. Aside from investigations of spheres, disks, and long cylinders described by SCHILLER [1932, p. 376] and WHITE [1946], few systematic data are available. Therefore, controlled laboratory studies of the resistance to motion of prismatic, cylindrical, double conical, and ellipsoidal particles were conducted at the University of Iowa to evaluate the effects of other shape properties. Stability of orientation, the practical upper limit to the Stokes range, and the effect on resistance if this limit is exceeded, all were investigated. The results of these experiments as well as part of the foregoing analysis, were submitted by the second author in dissertation form [MALAIKA, 1949] to the Graduate College of the University of Iowa in partial fulfillment of the requirements for the degree of doctor of philosophy.

For each of the four geometrical types selected, particles with three ratios (4:1, 1:1, 1:4) of length to the two equal normal dimensions were machined. The nominal diameter of the particles ranged from 0.0075 ft to 0.023 ft, the form and size of particles representing each shape being shown in Figure 2.

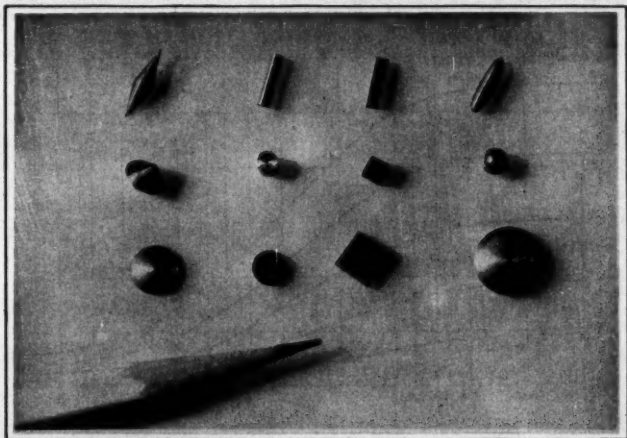


Fig. 2--Representative particles used in experimentation

particle was also weighed to the nearest 0.001 gm on a Chain-o-matic balance. Synthetic lubricants furnished by the Standard Oil Companies of Indiana and California were used, a range of kinematic viscosity from 0.005 to 0.3 ft²/sec being obtained. The specific gravity and viscosity of the oils were determined with a Mohr-Westphal hydrometer and a Hoppler precision viscosimeter, respectively. During the experiments, the oils were contained in a cylindrical glass jar eight inches in diameter and 18 inches high, and a constant temperature was maintained by means of a thermostatically controlled water bath.

Fall velocities from stop-watch determinations of the time required for a particle to fall a precisely delineated distance were reliable for velocities less than 0.1 fps. For determining higher velocities, stroboscopically lighted photographs of the particle superimposed on a scale subsequently photographed at the line of descent made reliable determinations possible. A submerged magnetic-release mechanism was used in obtaining the desired particle orientation.

The stability of particle orientation was found to depend upon the relative magnitude of inertial effects. For Reynolds numbers within the Stokes range, any orientation was stable, so that a particle would retain its initial orientation as it fell. However, for Reynolds numbers above a critical value, which varied somewhat with shape, a single stable position existed. Particles dropped in other positions at Reynolds numbers greater than approximately 0.1 invariably tended to orient themselves in this one position. For the symmetrical particles tested, the stable position was the one for which the maximum principal cross-sectional area was normal to the direction of motion, a result also observed by KRUMBEIN [1942] and KUNKEL [1948]. In almost all of the experiments, both within and above the Stokes range, the one stable position was used in order to provide continuous results over as wide a range of the Reynolds number as possible. Particles which were asymmetric, even by small amounts, had a preferred position in the Stokes range as well. In fact, the stability of orientation of the particles dropped in several positions was used as an experimental indication of symmetry.

Because the effects of viscous drag are widespread, a boundary to the fluid exerts an appreciable influence on the motion of the particle even if the particle is small compared to the distance to the boundary. In a recent study [McNOWN and Others, pending] the effect of cylindrical-container wall on the settling velocity of spheres was determined for diameter ratios between zero and unity, and for Reynolds numbers from zero to 1000. For relatively small particles [$D/D_0 < 0.25$] and for negligible inertial effects, the correction factor K for spherical particles was as follows

$$K = 1 + 9D/4D_0 + (9D/4D_0)^2 \dots \dots \dots (7)$$

in which D and D_0 are the diameters of the particle and the container, respectively. For a given diameter ratio the value of K was found to decrease with increasing Reynolds number as shown in Figure 3. The boundary influence was shown to be primarily a restriction on the upward flow of the

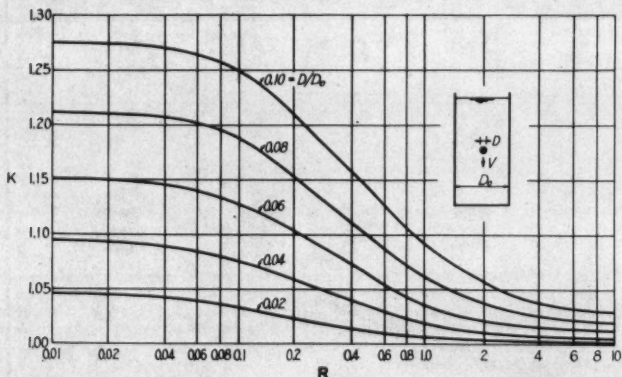


Fig. 3--Effect of cylindrical boundary on resistance of spherical particles

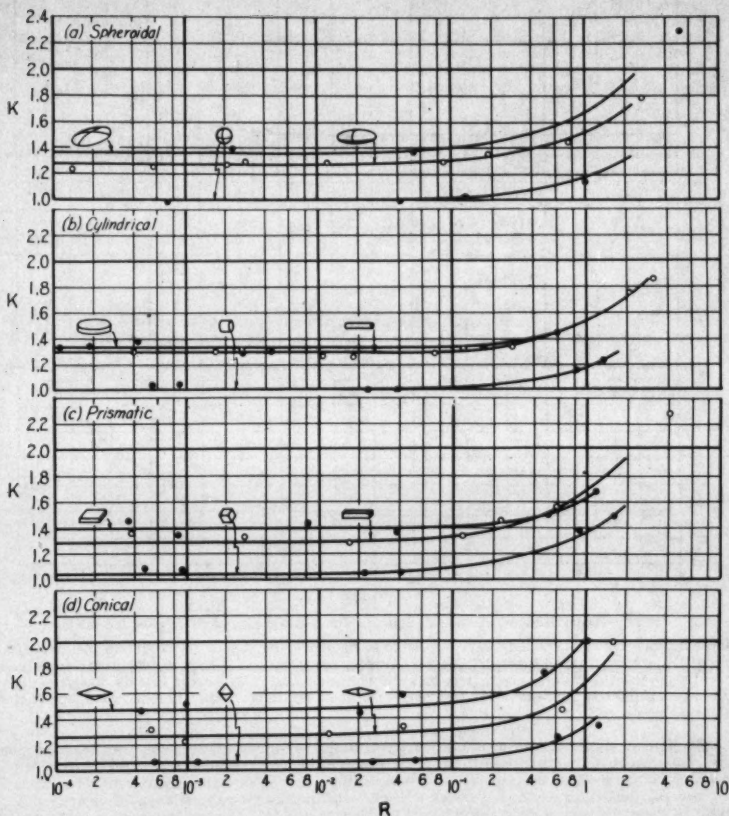


Fig. 4--Experimental results grouped in accordance with type of shape

fluid displaced by the settling particle. Therefore, the results for spheres were assumed to apply to particles of other shapes, the square root of the ratio of the projected area of the particle to the area of the cylinder being used as the diameter ratio. Corrections for this effect were as low as a few tenths of one per cent and seldom exceeded five per cent.

The experimental results are shown in Figure 4, in which K (corrected for boundary effects) has been plotted against the logarithm of the Reynolds number for each shape. A family of curves has been drawn for each type of shape and definite systematic trends are evident. The horizontal portions of the curves indicate the limiting values of K for very low Reynolds numbers. Inertial effects are seen to cause significant increases in the resistance coefficient as the Reynolds number increases. The upper limit to the Stokes range, which can only be set arbitrarily, is approximately 0.05 in each case. Although there are small differences between the four families of curves, their

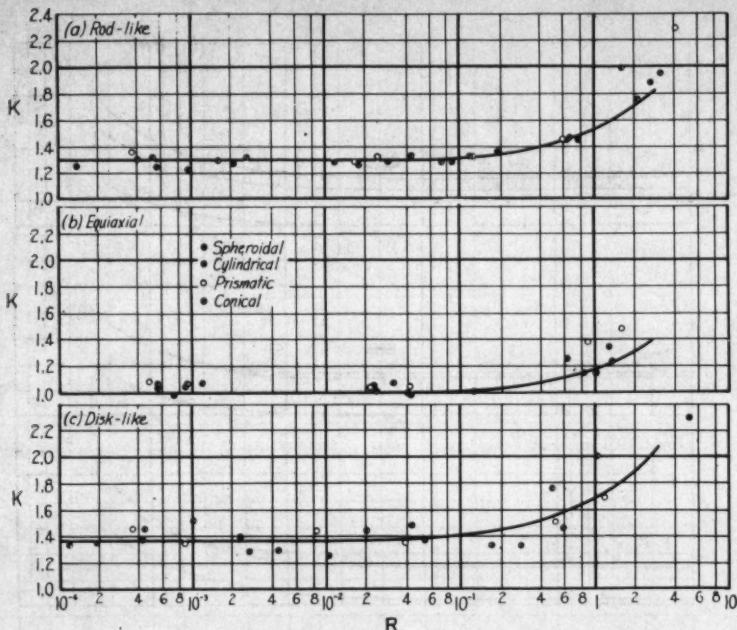


Fig. 5--Experimental results grouped in accordance with particle proportions

similarity is striking. The data were replotted in Figure 5, the results for particles of the same proportions being grouped together, and the curves were drawn for the spheroidal particles only. Even though the shape varies from prismatic to double conical, it is evident that the analytical results are sufficiently representative to make possible estimates for other shapes, which are accurate within ten per cent.

Significance of various shape parameters:--Although numerous shape factors have been proposed by various investigators [KRUMBEIN, 1943], the simplified axis ratios used in Figure 1 compare favorably both in significance and ease of determination. The most significant parameters which have been suggested for use are sphericity, which is defined as the ratio of the surface area of a sphere of the same volume as the particle to the surface area of the particle; roundness, the ratio of the average radius of the corners and edges of a particle to the radius of a circle inscribed in the maximum projected area of the particle; and circularity, the ratio of the circumference of a circle whose area equals the projected area of the particle to the circumference of the projected area of the particle. Unfortunately, none of these factors is easily evaluated even for as simple a body as the ellipsoid. Furthermore, only circularity is correlated in any way with particle orientation, and it depends solely upon the characteristics of the projected area. For low Reynolds numbers the effect of roundness, as well as surface roughness, is undoubtedly very slight.

The ratios of the principal axes, $a/\sqrt{bc}$ and b/c as used for the ellipsoids in Figure 1, are shape factors which are both significant and readily evaluable. The plots in Figure 5 indicate that particles with the same orientation and the same axis ratios have approximately the same resistance regardless of variations in form. The first parameter, $a/\sqrt{bc}$, is roughly equivalent to sphericity, as indicated by Krumbein [MALAIKA, 1949], except that it includes the effect of orientation, since a is always in the direction of motion; its value therefore exceeds unity for particles elongated in

the direction of motion. The product of b and c is preferable to either b or c alone, since the ratio of its square root to a is a measure of relative elongation in the direction of motion. The ratio b/c is equivalent in a similar way to circularity, but is more simply determined. It thus follows that once the proportions and orientation of a particle are known, the resistance and settling velocity can be estimated from Figure 1 within perhaps ten per cent for low Reynolds numbers. If the orientation is not known, somewhat less accurate values can be obtained by averaging the three possibilities.

Secondary shape effects are apparent from Figures 4 and 5. For comparable disk-like particles ($a = b = c$), the double cone has a greater resistance and the cylinder a smaller resistance than the ellipsoid. The projected area for a given volume, which must affect the resistance, is greater for the double cone and less for the cylinder than that of the ellipsoid. The projected area of the rectangular prism is the same as that of the cylinder, but, as might be expected, the square cross section leads to a greater resistance than the circular cross section. Sharp edges are apparently unimportant unless the Reynolds number is sufficiently high for form drag to be effective. Because of the uncertainties in determining shape and orientation, the approximate effects indicated by the axis ratios are sufficient for estimation of shape effects.

Applications--Approximate methods of evaluating shape effects are applicable to studies in many fields. In analyses of the transportation, scour, and deposition of sediment, the particle settling velocity is a variable of primary importance. Although the effect of shape is only one of a number of uncertainties, its determination provides worthwhile information. This is particularly true in estimations of the rate at which a reservoir will fill with sediment. In current practice, the distribution of the particle settling velocities is determined, and the sizes or volumes are computed therefrom, the spherical shape being assumed. As long as the particles are reasonably close to the spherical shape (refer to Figure 1), no serious error results from this practice. However, for predominantly flat or rod-like shapes the volume of a particle having a given settling velocity is much greater. Hence estimates of the quantity of sediment based on fall velocities might be in error if spherical shape is assumed.

Abrasives, particularly those of the finer grades, are sorted by one of several processes which depend upon settling velocity. Since the particle sizes of abrasives must be essentially constant, shape effects may well be important. Occasional particles with one or two larger dimensions would, of course, be undesirable, even if the settling velocity were correct. Still another application of shape studies is found in the determination of the charge on the particles by the Hopper and Laby method. Fine particles of dust or powder are dropped between charged plates, and the angle of drift is assumed to be a measure of the particle charge if the rate of fall is known. Since orientation, asymmetry, and shape may all affect the results, such a study can only be interpreted if various shape characteristics are known [KUNKEL, 1948].

In the fields mentioned, and in numerous others for which particle settling velocity is a significant factor, shape effects are often important. Improved accuracy can be obtained if representative samples of the particles are examined microscopically, since knowledge of the axis ratios of the particles makes possible an estimate of the settling velocity which is more nearly correct than one based on the Stokes equation.

Conclusions--Extension of existing theoretical analyses for the motion of ellipsoids at low Reynolds numbers has provided a quantity of useful information on primary shape effects. Furthermore, approximately the same coefficients of resistance have been found for particles of given axis ratios and orientation but various shapes. Hence, the theoretical results made available in this study can be used in estimating the settling velocities for particles of virtually any shape. The ease of application and broad scope of these analyses make possible the determination of shape effects in many fields of scientific and practical significance.

Acknowledgments--This study was suggested by E. W. Lane of the United States Bureau of Reclamation. Hunter Rouse, director of the Iowa Institute of Hydraulic Research, and E. Y. Hsu, research associate, contributed valuable advice and assistance. The project was partially supported by the Office of Naval Research under Contract No. N8onr-500.

References

- KRUMBEIN, W. C., Settling velocity and flume behavior of non-spherical particles, *Trans. Amer. Geophys. Union*, pp. 621-633, 1942.
KRUMBEIN, W. C., Fundamental attributes of sedimentary particles, *Proc. Second Hydr. Conf., Univ. of Iowa Studies in Engineering*, Bull. 27, pp. 318-331, 1943.

- KUNKEL, W. B., Magnitude and character of errors produced by shape factors in Stokes' law estimates of particle radius, *J. App. Phys.*, v. 19, pp. 1056-1058, 1948.
- LAMB, H., *Hydrodynamics*, Dover Publications, New York, 1945.
- MALAIKA, J., Effect of shape of particles on their settling velocity, Ph.D. dissertation, Dept. of Mechanics and Hydraulics, Univ. of Iowa, Feb. 1949.
- McNOWN, J. S.; LEE, H. M.; McPHERSON, M. B.; and ENGEZ, S. M., Influence of boundary proximity on the drag of spheres, *Proc. VIII Int. Cong. of App. Mech.*, London, (pending).
- PEIRCE, B. O., *A short table of integrals*, 3rd revised ed., Ginn and Co., 1929.
- SCHILLER, L., *Handbuch der Experimentalphysik*, v. 4, pt. 2, 1932.
- WHITE, C. M., The drag of cylinders in fluids at slow speeds, *Proc. R. Soc., A.*, v. 186, 1946.

Iowa Institute of Hydraulic Research,
State University of Iowa,
Iowa City, Iowa

(Manuscript received April 18, 1949; presented at the Thirtieth Annual Meeting, Washington, D. C., April 21, 1949; open for formal discussion until July 1, 1950.)

SUMMER RAINFALL CHARACTERISTICS IN NORTHERN UTAH

A. R. Croft and Richard B. Marston

Abstract--This paper presents information on the frequency, depth, intensity, and areal extent of July-August cloudburst type rainfall on part of the Wasatch Mountains in northern Utah. Intensities of some rainfall bursts on the mountain land are compared with those at valley stations.

Introduction--Torrential rains, frequently called cloudbursts, are a common event during July and August on the mountains of Utah. These rains are known to be a potent eroding agent and to be capable of generating violent debris floods. Because very few recording rain gages have been operated at mountain stations, however, there is only meager information on the frequency, depth, intensity, duration, and areal characteristics of this type of rainfall at high elevations.

Especially destructive mud-rock floods occurred in northern Utah in the summers of 1923 as reported by PAUL and BAKER [1923] and in 1930 as reported by CANNON [1931]. These events led to the start of a watershed research program in 1933 on a portion of the Wasatch Mountains near Farmington, Utah. This program included studies of watershed conditions and improvement measures, phases of which have been reported by BAILEY, FORSLING, and BECRAFT [1934] and by BAILEY, CRADDOCK, and CROFT [1947]. Because of their importance in watershed management, the program also included a study of summer rainfall characteristics, some results of which are reported in this paper.

Study area--The study area embraces the watersheds of seven perennial streams that drain about 36 sq mi of the western slope of the Wasatch mountains about midway between Ogden and Salt Lake City. Six of the streams - Centerville, Parrish, Barnard, Ford, Davis, and Steed - rise near

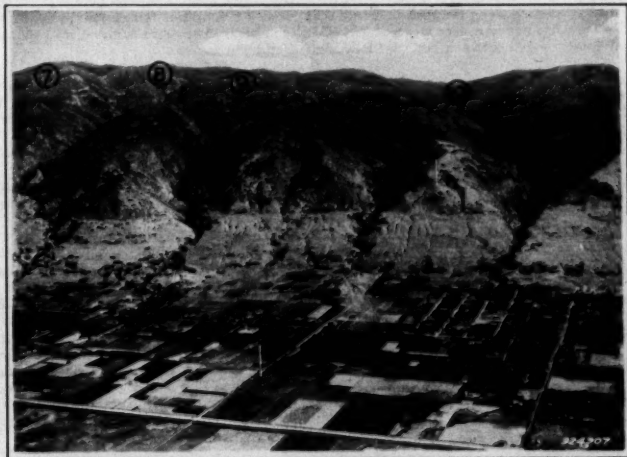


Fig. 1--The Wasatch Mountain front near Centerville, Utah, showing (left to right) head of Steed, and canyons of Ford, Barnard, Parrish, and Centerville drainages and the location of rain gages 7, 8, 9, 10, and 11

a north-south mountain crest at elevations of 8500 to 9300 ft and flow westward in high gradient channels to a common valley floor that forms part of the eastern shore of the Great Salt Lake at an elevation of 4200 ft (see Fig. 1). The seventh and most northerly stream, Farmington, originates in a basin east of the mountain crest at an elevation of 9300 ft. This creek flows northward about a mile, then turns west, crossing the mountain range through a canyon about 1600 ft deep to reach the valley at the same elevation as the other streams.

Table 1--Recording rain gage stations,
Wasatch Experimental Watersheds

Name	Established	Elevation
		ft
Halfway (1) ^a	1941	8800
Bigler (2)	1941	8200
Farmington Flats (3)	1942	7600
Rice (4)	1936	7000
Mud (5)	1939	8400
Miller (6)	1941	8200
Steed (7)	1946	8500
Ford (8)	1946	8200
Parrish (9)	1936	8150
Centerville (10)	1942	8200
Goat (11)	1939	6000
Warehouse (12)	1939	4300

^aNumbers in parentheses are key to location of stations shown in Figures 2 and 5.

Rainfall record-taking began in 1934 when four standard gages of the United States Weather Bureau were set up near the mountain crest in the headwaters of Centerville, Parrish, and Ford Canyons. Records of rainfall intensity started in 1936 at which time Fries weighing-type recording gages were installed at the Parrish Station and at the Rice Station in Farmington Canyon. Three more recording rain gages were added to the network in 1939, three more in 1941, and two more in 1942 and in 1946. Ten of the recording gages were distributed at about one-mile intervals along the west slope of the mountain near the crest and around the upper portion of Farmington Canyon. Two were located at or near the mountain base, about six miles apart. The station designation, date of establishment, and elevation of the 12 recording gages are given in Table 1 and their locations are shown in Figure 2.

Some point rainfall characteristics--At

Parrish, the station of longest record, there have been 153 July-August rainfalls in the 14-year period 1934-1947, an average of about 11 storms per season. A storm, as used in this paper, is a period of rainfall preceded and followed by two hours without rain.

Rainfall depth in each of 118 of the 153 storms, or 77 per cent, was less than 0.25 inch. In 25 storms, rainfall depths were between 0.26 and 0.50 inch. Of the other ten storms, less than seven per cent of the total number, five were of 0.51-0.75 inch depth, two were in the 0.76-1.00 inch depth class, and three ranged between 1.01 and 1.26 inches in depth.

Rainfall intensity records were obtained for 124 of the 153 storms at the Parrish Station in the period 1936-1947. Records of four other storms were missed because of clock stoppage. Rainfall amounts were determined from the recorder charts by five-minute intervals. The five-minute period of maximum rainfall was used as a base for determining subsequent and antecedent five-minute amounts. Rainfall charts made by clocks either fast or slow were adjusted to correct time.

Maximum rates of rainfall for five-minute periods in the 124 storms of intensity record at the Parrish Station ranged from 0.02 to 6.84 in/hr. as shown in Table 2. It will be seen that there has been a strong tendency for rainfall rates to increase with amount of rain.

The rains at this station differed markedly in their effectiveness in causing overland flow and soil erosion. Sixteen surface runoff plots from 1/40 to 1/10 acre in size equipped to measure runoff and eroded soil were established in 1934.

Table 2--Number of storms by inch-depth
classes and maximum five-minute intensity
classes at Parrish Station, 1936-1947

Depth classes in	Intensity classes inches per hour							
	0-1	1-2	2-3	3-4	4-5	5-6	6-7	
0.00-0.25	91	3	..	..	..	..	..	
0.26-0.50	12	7	3	..	..	..	..	
0.51-0.75	..	1	2	..	..	..	..	
0.76-1.00	..	1	1	..	..	..	..	
1.01-1.26	..	..	..	..	1	1	1	

Records from these plots show that rains at rates up to about 1.50 in/hr were relatively non-effective; whereas, rates in excess of this amount, under condition of depleted plant cover, were capable of producing substantial amounts of overland flow and of causing serious soil losses. Accordingly, rainfalls with five-minute intensity rates of 1.5 in/hr or more are called effective rainfalls.

Effective rainfall--There have been twelve July-August storms during the period 1936-1947 that produced rainfall rates in excess of 1.50 in/hr at one or more of the recording rain gage stations. Only one or two records of high

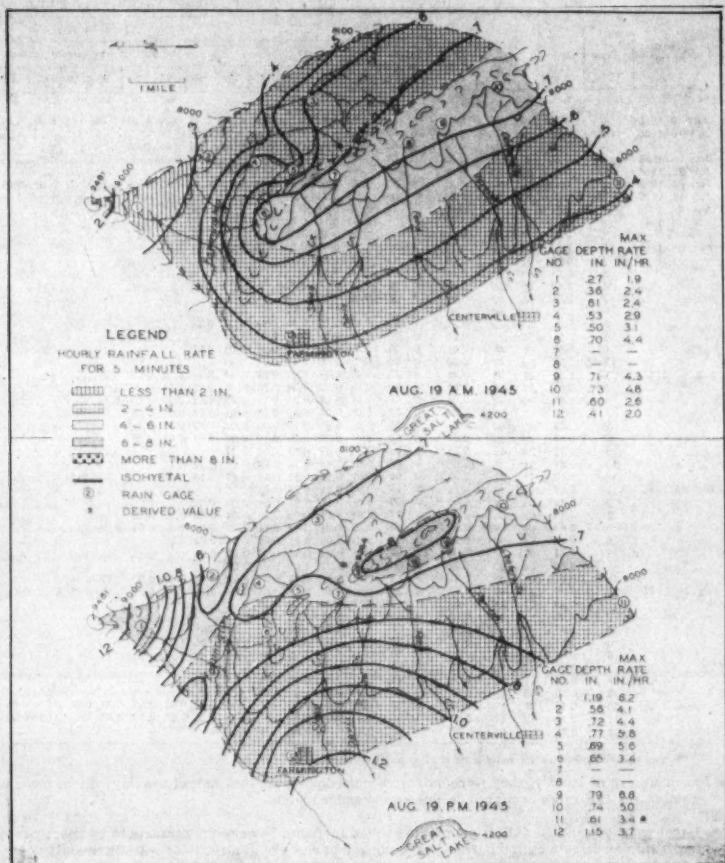


Fig. 2--Depth-area and intensity-area of rainfall bursts
 at about 7^h30^m and 21^h30^m August 19, 1945

Intensity rainfall were obtained during the first eight storms due mainly to the limited number of recording gages in operation. High-intensity rainfall was recorded at from six to twelve stations during the last four of these major storms. In all, 49 records have been obtained of the twelve effective storms (see Table 3).

The total-storm gage measurements of these major storms ranged from 0.34 to 1.52 inches. Total duration ranged from 30 min to about 12 hr. Nine of the twelve effective storms occurred in after noon, with five of them coming before 18^h00^m. Three storms occurred in the period midnight to 6^h00^m and one in the period 6^h00^m to 12^h00^m. Thus, although effective storms occurred during

Table 3--Characteristics of 12 effective summer rains at various recording

Date of storm	Gage	Depth	Time of start	Pre-burst		First burst												
				Depth	Duration	Rainfall by five-minute periods												
						1	2	3	4	5	6	7	8	9	10	11	12	
		inch	h m	in	h m	in	in	in	in	in	in	in	in	in	in	in	in	
July 8, 1936	4	0.93	12 45	0.23	4 50	0.04	0.02	0.04	0.06	0.10	0.13	0.07	0.06	0.06	0.02	0.01	0.01	
July 10, 1936	4	0.88	15 40	0.00	0 00	0.03	0.04	0.09	0.14	0.12	0.06	0.02						
	9	1.14	15 39	0.00	0 00	0.22	0.30	0.42	0.09	0.04	0.02	0.01	0.01					
July 16, 1936	9	0.89	17 25	0.00	0 00	0.02	0.14	0.22	0.17	0.23	0.07	0.01						
July 27, 1936	4	0.11	14 57	0.00		0.21	0.17	0.06	0.02	0.02	0.02							
July 28, 1936	4	1.10	14 51	0.01	0 15	0.02	0.07	0.24	0.18	0.15	0.16	0.05	0.07	0.10	0.02	0.02	0.01	
July 13, 1937	9	0.34	21 25	0.00	0 00	0.01	0.05	0.20	0.02									
Aug. 10, 1943	9	0.44	23 45	0.00		0.10	0.19	0.05	0.01	0.05	0.04							
Aug. 18, 1945	9	0.37	22 00	0.00		0.03	0.20	0.01										
	3	0.48	22 05	0.00		0.28	0.03											
Aug. 19, 1945	1	0.63	02 00	0.30	5 32	0.01	0.01	0.03	0.16	0.03	0.01	0.01						
	2	0.76	02 30	0.02	3 35	0.06	0.10											
	3	1.14	05 35	0.01	0 29	0.07	0.01											
	4	1.10	05 50	0.00	0 00	0.03	0.18	0.02										
	5	1.21	05 52	0.00	0 00	0.02	0.34	0.02										
	6	1.29	03 00	0.02	2 50	0.06	0.17	0.02										
	9	1.08	05 42	0.01	1 45	0.07	0.22	0.36	0.04	0.06	0.01							
	10	1.04	07 27	0.00	0 00	0.02	0.39	0.40	0.01									
	11	0.87	08 45	0.01	0 30	0.02	0.23	0.26	0.07	0.01	0.01							
	12	0.87	05 48	0.00	0 00	0.09	0.03	0.01										
Aug. 19, 1945	1	1.34	21 03	0.06	0 35	0.01	0.01	0.01	0.52	0.38	0.35	0.09	0.03	0.01				
	2	0.81	21 00	0.04	0 30	0.01	0.01	0.34	0.05	0.06	0.06	0.04	0.01					
	3	1.08	20 52	0.06	0 41	0.01	0.06	0.37	0.18	0.02	0.02	0.03	0.02	0.22				
	4	1.11	21 01	0.03	0 30	0.01	0.02	0.48	0.16	0.01	0.02	0.05	0.01					
	5	1.29	21 00	0.04	0 35	0.01	0.47	0.13	0.02	0.02	0.03	0.01						
	6	1.40	20 42	0.02	0 40	0.01	0.02	0.38	0.19	0.06	0.01	0.07	0.02					
	9	1.12	20 46	0.02	0 45	0.08	0.57	0.11	0.02	0.01								
	10	0.84	21 29	0.00	0 00	0.07	0.43	0.19	0.02	0.01	0.01							
	12	1.52	21 28	0.00	0 00	0.02	0.14	0.21	0.28	0.37	0.10	0.06						
Aug. 20, 1945	1	0.87	05 02	0.02	1 45	0.04	0.12	0.22	0.01									
	2	0.75	04 45	0.00	0 00	0.01	0.10	0.01	0.04	0.01	0.01							
	3	0.50	05 06	0.07	2 37	0.02	0.11	0.05	0.20	0.01	0.02	0.01	0.01					
	5	0.82	04 58	0.05	2 40	0.03	0.01	0.03	0.14	0.23	0.04	0.04	0.02	0.02				
	6	0.52	04 50	0.10	2 55	0.01	0.08	0.15	0.07	0.05	0.02	0.01						
	9	0.52	05 39	0.06	2 00	0.01	0.05	0.24	0.12	0.02	0.01							
	10	0.56	04 00	0.06	3 50	0.08	0.31	0.01	0.02	0.01								
	12	0.41	04 55	0.02	2 45	0.01	0.05	0.03	0.04	0.02	0.02	0.03	0.03	0.02	0.14			
Aug. 10, 1947	1	0.79	11 55	0.10	0 30	0.05	0.41	0.04	0.03	0.01	0.05	0.01	0.01	0.01	0.01	0.01	0.01	
	2	0.86	11 49	0.05	0 40	0.58	0.07	0.02	0.02									
	3	0.76	11 35	0.03	0 40	0.01	0.41	0.05	0.01									
	4	1.03	11 43	0.02	0 30	0.05	0.70	0.06	0.01	0.04	0.01							
	5	0.63	11 45	0.01	0 30	0.04	0.35	0.02	0.05	0.02	0.01	0.02						
	6	0.94	11 43	0.03	0 30	0.05	0.52	0.02	0.04	0.03								
	7	0.53	11 25	0.02	0 45	0.28	0.04	0.02	0.01									
	8	0.48	11 27	0.04	0 45	0.21	0.03	0.01	0.01									
	9	0.85	12 18	0.00	0 00	0.23	0.09	0.01	0.01									
	10	0.79	09 17	0.06	3 02	0.18	0.10	0.05	0.03	0.03	0.03	0.02	0.01	0.01	0.06	0.04	0.01	
	11	0.83	12 17	0.00	0 00	0.37	0.05	0.01	0.01	0.03	0.05	0.02	0.02	0.02	0.10	0.03	0.02	
	12	0.86	11 40	0.06	0 33	0.41	0.09	0.01	0.01	0.01								

*Includes one 0.16 inch low intensity burst of 20 minutes duration

all four quarters of the day, they were more frequent during the last half of the day. Also, most of the greatest rainfall rates occurred between noon and midnight.

Burst characteristics--All of the storms listed in Table 3 were characterized by short periods of intense rainfall herein called bursts and by longer periods of gentle, intermittent rainfall designated as pre-burst or non-burst. Approximately 80 per cent of the rainfall in these storms occurred as burst rainfall, the remainder occurring in pre-burst and non-burst periods. Non-burst rainfall extended over periods of from ten minutes to 12 hours. The bursts lasted as long as 85 minutes and a few lasted only ten minutes. In most cases, the great bulk of the burst rainfall occurred within 30 minutes.

Most of the storms had but one major burst. In 1945, however, there were four successive storms in which double bursts were registered at one station or more. In two of these storms, August 18 and several of August 19, about twice as much rainfall occurred in the first burst as in the second. In the other two storms, first of August 19 a.m. and August 20, about two to three times as much rainfall occurred in the second burst than in the first at stations recording both bursts.

Table 3 shows also, that there was a total of 65 periods of burst rainfall in the 49 records of effective storms. The maximum depth at any station was 0.70, 0.88, 1.13, and 1.26 inches for 5, 10,

rain gage stations, Wasatch Experimental Watershed, 1936 to 1947

					Non-burst		Second burst										Non-burst		Time of end	Storm duration
13	14	15	16	17	Depth	Dura-tion	Rainfall by five-minute periods										Depth	Dura-tion		
in	in	in	in	in	in	h m	1	2	3	4	5	6	7	8			in	h m	h m	h m
0.01	0.02				0.03	2 45													21 30	8 45
					0.34	5 45													22 00	6 20
					0.03	0 50													17 09	1 30
					0.03	0 40													18 40	1 15
					0.01	0 25													15 52	0 55
					0.00	0 00													18 06	1 15
					0.06	0 45													22 06	1 15
					0.00	0 00													00 15	0 30
					0.13	2 03													00 18	2 18
					0.19	0 47	0.01	0.11	0.01								0.06	3 18	02 23	4 18
					0.17	8 38													14 45	10 45
					0.00	1 38	0.33	0.08	0.30	0.02	0.01	0.01					0.23	6 12	14 15	11 58
					0.01	1 24	0.01	0.09	0.30	0.18	0.10	0.02					0.42	5 38 ^a	13 54	8 29
					0.00	1 30	0.01	0.02	0.12	0.34	0.09	0.03	0.01				0.35	6 00	14 00	8 10
					0.00	1 22	0.01	0.09	0.36	0.11	0.03	0.01	0.01				0.41	5 48	13 52	8 00
					0.00	1 30	0.01	0.17	0.37	0.10	0.02	0.01	0.02				0.32	5 45	13 48	10 45
					0.36	8 00													13 56	8 14
					0.32	10 08													17 58	10 28
					0.08	1 06														
					0.00	1 21	0.01	0.02	0.07	0.18	0.12	0.02					0.13	7 08	15 00	9 12
					0.10	0 40													22 53	1 50
					0.00	0 30	0.04	0.09	0.04	0.01							0.02	2 20	01 10	4 10
					0.00	0 17	0.05	0.18	0.05	0.02									22 58	3 03
					0.00	0 24	0.10	0.15	0.04	0.03									22 58	1 54
					0.00	0 18	0.04	0.05	0.31	0.11	0.01						0.04	2 35	01 18	4 18
					0.00	0 23	0.11	0.44	0.11	0.03							0.03	3 15	02 00	5 18
					0.00	0 37	0.17	0.04	0.04	0.01							0.05	2 46	01 39	4 53
					0.11	3 51													01 50	4 21
					0.01	0 23	0.03	0.17	0.08	0.07									23 43	1 18
					0.01	0 33	0.08	0.11	0.06	0.04	0.06	0.07	0.08	0.01					08 25	3 23
					0.10	2 30	0.01	0.18	0.05	0.05	0.09	0.03	0.03	0.01			0.02	1 06	09 30	4 45
																			08 23	3 17
					0.01	1 10													09 33	4 36
					0.03	1 10													09 30	4 40
					0.01	0 15													08 34	3 45
					0.04	1 20													09 35	5 35
					0.00	0 00													08 30	3 35
					0.03	0 20													13 50	1 55
0.01					0.12	1 25													14 14	2 25
					0.25	4 15													17 00	2 25
					0.12	1 00													13 43	2 00
					0.10	0 55													13 45	2 00
					0.14	1 20													13 58	2 18
					0.16	4 00													16 30	8 06
					0.18	4 02													16 34	8 07
					0.31	1 35													14 13	1 58
					0.03	0 50													14 34	8 17
0.02	0.02	0.02	0.02	0.01	0.01	0 10													13 52	1 25
0.01	0.04	0.02	0.01	0.01	0.01	0 50													13 33	1 53
					0.08	0 55														

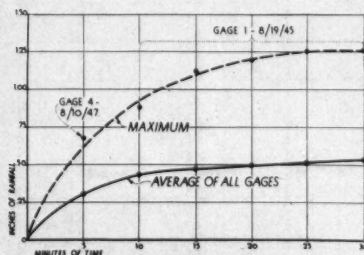
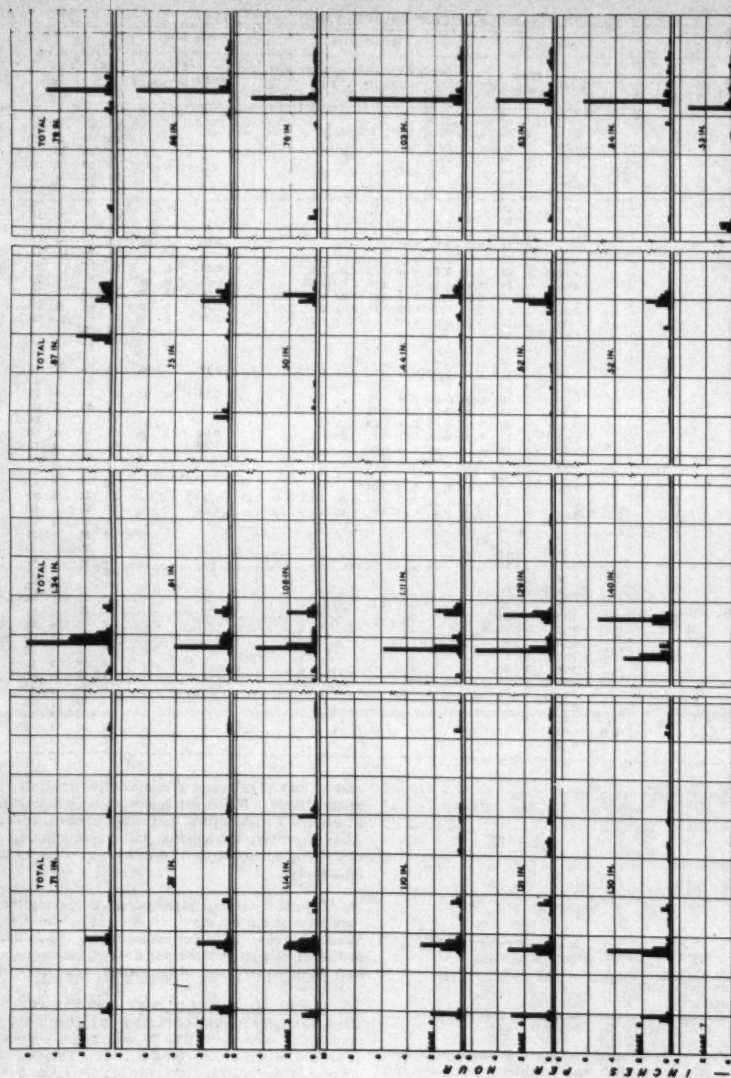


Fig. 3--Maximum and average maximum 30-minute rainfall by five-minute periods for 65 bursts shown in Table 3

and 15 and 30 minutes of consecutive rainfall, respectively. These rates are shown graphically in Figure 3 with station and dates of occurrence. Also shown are the average maximum amounts of rain by consecutive five-minute periods up to 30 minutes.

Greatest rainfall rates occurred during the fore part of the bursts in 60 per cent of the 65 burst records. They occurred during the middle of the burst period in 37 per cent of the cases and, in three per cent of the cases, near the end.

Synchronization of bursts--The records show that burst rainfall of relatively high intensity may occur over the entire 36-square mile area at about the same time (see Fig. 4). The two storms of August 19, 1945, for example, each had two bursts in which the maximum five-minute



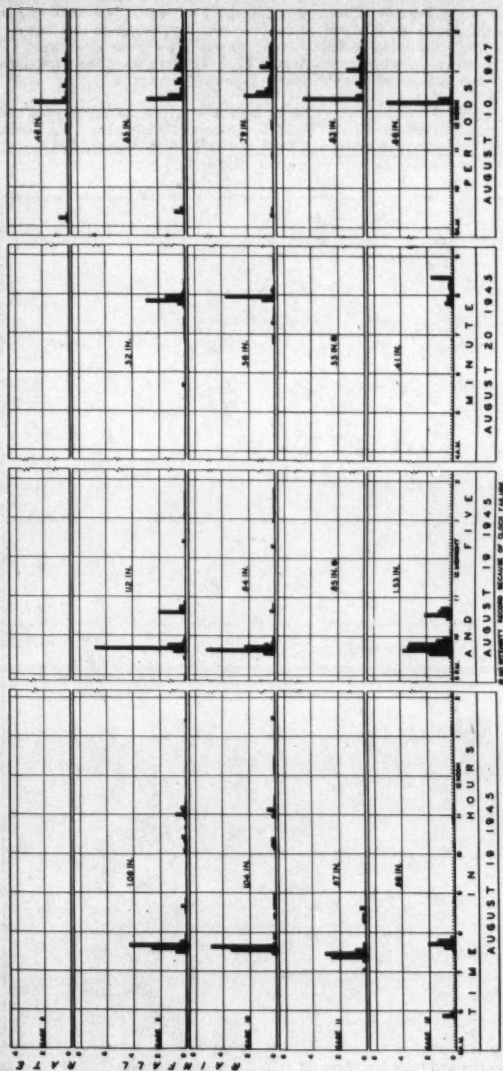


Fig. 4--Burst synchronization during convective type rains

rainfall periods of the several stations were separated by less than 15 minutes. The same was true for all mountain stations during the single burst storm on the following day, though in that storm, the highest intensity of rain at the valley station occurred about 30 min after peak intensities at the mountain stations. During the single burst storm of August 10, 1947 there was also a maximum interval of about 15 minutes between stations when peak burst intensities occurred.

Depth intensity-area relations--The multiple records of the three major storms in 1945 and the one in 1947 also throw light on the areal extent of burst rainfall depths and intensities. The specific bursts here considered are those that occurred at about 7^h30^m and 21^h30^m on August 19, 1945, at about 8^h00^m on August 20, 1945, and at about 12^h15^m on August 10, 1947.

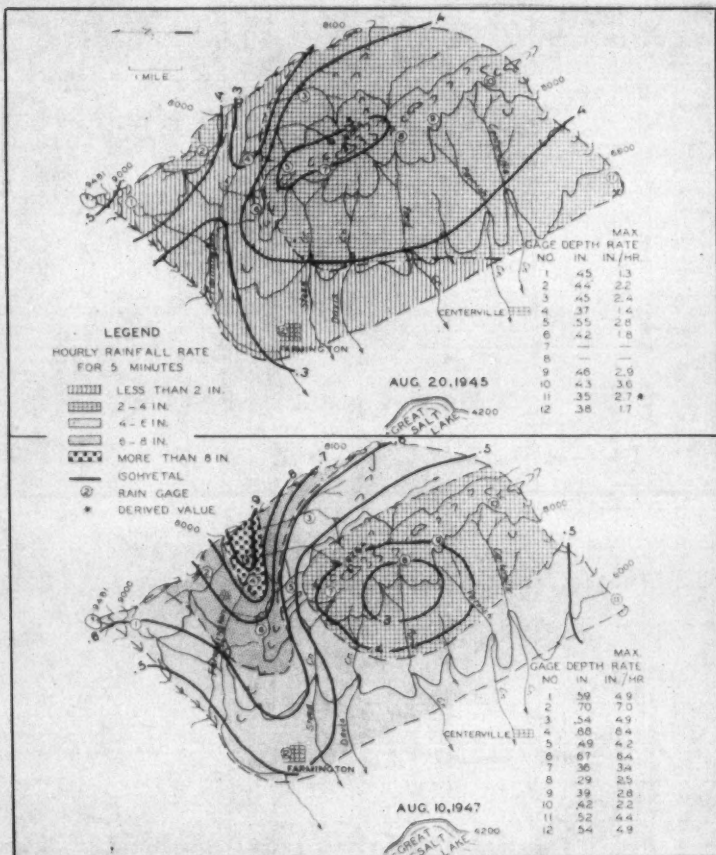


Fig. 5--Depth-area and intensity-area of rainfall bursts at about 8^h00^m August 20, 1945 and 12^h15^m August 10, 1947

The burst at 7³⁰am during the storm of August 19, 1945 centered along the mountain crest south of Farmington Canyon where about 0.70 inch of rain fell (Fig. 2). The amount of rainfall decreased westward to 0.41 inch at Farmington and northward along the high mountain crest to 0.27 inch near Station 1. Intensities of four to six inches per hour occurred on a ten-square-mile area above about 7000 ft elevation on the west mountain slope. On 25 sq mi through Farmington Canyon and along the mountain base, intensity was in the two to four inches per hour class and on about one square mile near Station 1 intensity dropped to less than two inches per hour.

The burst at 2¹⁰pm on August 19 had three high-intensity rainfall centers in contrast to only one for the morning storm (see Fig. 2). Two of these occurred on the mountain crest, one north and one south of Farmington Canyon where about 1.2 and 0.8 inch of rain fell, respectively. The other center was in the valley near the town of Farmington where 1.15 inches of rain fell. Rainfall rates were greater than two inches per hour over the entire 36-sq mi area. Two zones of about a square mile each with six to eight inches per hour intensity appeared to coincide with the two storm-depth centers on the mountain crest. Most of the remaining area above 7000 ft elevation, about 14 sq mi, received four to six inches per hour intensity. On about 20 square mi of mountain front below about 7000 ft elevation, intensity was two to four inches per hour.

The storm of August 20, 1945, had lower rainfall depths and intensities than storms on the day before and, except at Stations 1 and 2, was a single-burst storm (see Fig. 5). As in the storms of the previous day, rainfall was light in Farmington Canyon but heavy on the mountain crest to the north and south where about 0.5 inch of rain fell. Intensities of two to four inches per hour occurred over about 20 sq mi, mainly above 6000 ft elevation south of Farmington Canyon. Intensity was less than two inches per hour on about 14 sq mi, including most of Farmington Canyon and the lower mountain front below about 6000 ft elevation.

The single burst storm of August 10, 1947 differed from those of August 1945 in that its burst centered over Farmington Canyon with a definite zone of light rainfall along the mountain crest to the south. Burst rainfall depth was as much as 0.88 inch in the canyon bottom but only 0.29 inch in the low-intensity storm center on the mountain crest. A record high intensity for the area of 8.4 inches per hour occurred at Station 4 in the bottom of Farmington Canyon. About one square mile in this vicinity, it appears, received rainfall in excess of eight inches per hour intensity. Rates of from six to eight inches per hour occurred on about five square miles in the deepest part of upper Farmington Canyon. An area of 19 sq mi with four to six inches per hour intensities included the remainder of Farmington Canyon and the mountain face below about 7000 ft elevation. On 11 sq mi along the mountain crest, in the vicinity of the center of minimum depth, intensities were two to four inches per hour.

The multiple records of these four storms show there was considerable variation in rainfall depth and intensity from place to place during individual bursts and between bursts. Though greatest depths and intensities tended to occur near mountain crests in three of the storms, their occurrence in a deep canyon bottom in one of the four storms indicates no consistent relationship to relief. It appears, in other words, that high-intensity rainfall may occur on all portions of this mountainous area. Moreover, the records show that rainfall rates in excess of eight inches per hour may occur on an area of about one square mile and that rates in excess of six, four, and two inches per hour may occur over as many as six, 25, and 35 square miles, respectively (see Table 4).

Table 4--Extent of rainfall^a of various intensities for storms of August 1945 and 1947

Rainfall intensity classes (in./hr)	Area of storm			
	Aug. 19, 1945, first storm	Aug. 19, 1945, second storm	Aug. 20, 1945	Aug. 10, 1947
	sq mi	sq mi	sq mi	sq mi
Less than 2	1	0	14	00
2-4	25	20	22	11
4-6	10	14	0	19
6-8	0	2	0	5
More than 8	0	0	0	1

^aThis is areal extent within the 36-sq mi area under study only, and does not include the whole storm area.

Observations following these storms revealed freshly cut rills in the soil and other signs of torrential rainfall on lands in the immediate vicinity of the study area. A mud-rock flood issued from Bairs Canyon, one mile north of Station 1 at about the same time the August 10, 1947 storm was registered in the rain gage network. This evidence indicates high-intensity rainfall occurred beyond the limits of the study area and suggests that the estimates of the areal extent of burst rainfall depths and intensities are probably conservative.

Moreover, at about the same time the morning storm on August 19, 1945 was recorded over the study area, a mud-rock flood occurred in Jump-off Canyon about 25 mi north. On the same day when the evening storm was recorded, a destructive flood occurred on the foothills near Salt Lake City, some eight miles south. These events suggest intense rainfall occurred over other portions of the northern Wasatch Mountains at about the same time as on the experimental area. Whether these outlying floods were caused by localized centers of the same storm or of other storms, is not known. It is possible, also, that there may have been other local high-intensity storm centers over areas where watershed conditions were not favorable for flood runoff.

Mountain and valley rainfall rates--A comparison of rainfall intensities was made between records at the mountain stations on the experimental area and (1) those at the Farmington (valley) station; and (2) those of valley stations throughout Utah.

During the double burst storm on the morning of August 19, 1945, a record of which was made at ten mountain stations, maximum intensity at Farmington was two inches per hour. At one mountain station it was also two inches per hour, but at five others it was about 2.5 inches per hour, and at three, more than four inches per hour. A similar comparison of all bursts that were recorded at various stations during the storms of August 1945 and 1947 show that about 75 per cent of the bursts at mountain stations had equal or higher intensities than bursts at the valley station in Farmington. The data indicate that for 1945 and 1947 storms, at least, rainfall intensities were considerably higher in the mountains than in the valley.

Precipitation at the mountain stations on the experimental area was also compared with that at the 18 valley stations from Cedar City, Utah, about 250 mi south, to Logan, Utah, about 50 mi north, for the period 1936 to 1947. The relation of five-minute precipitation to 30-minute precipitation was compared using 49 records at the mountain stations and 44 records from the valley stations, all with intensities higher than about two inches per hour (see Fig. 6). The amount of rain varied from about 0.2 to 1.15 inches at both mountain and valley stations. Rainfall rates, however, were greater in the mountains. For example, for valley stations, when maximum 30-minute precipitation increased from 0.22 to 1.15 inches, maximum five-minute precipitation increased only from 0.22 to 0.25 inch. Statistically, this relationship is not significant. At the mountain stations, on the other hand, with the same increase in 30-minute rainfall, the five-minute amounts increased from 0.18 to 0.55 inch. Here, the relationship is highly significant.

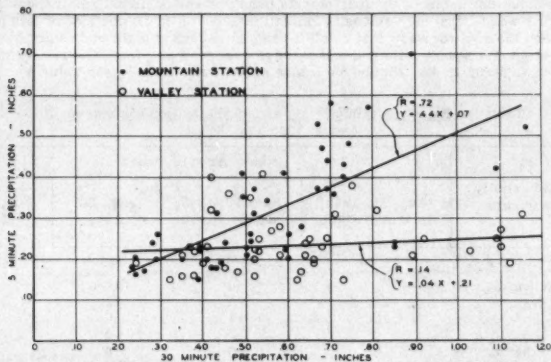


Fig. 6--The relation of 30-minute to five-minute rainfall at nine stations on the Wasatch Front and at 18 valley stations from Cedar City to Logan, Utah, 1936 to 1947

Although these mountain and valley intensity data are by no means conclusive, they strongly suggest that higher rainfall intensities may be expected on the windward slopes of the Wasatch Mountains than in the adjacent windward valleys. It is recognized that the areas are not truly comparable, the period of study is short, and that as longer and more comparable records become available these values may be considerably changed.

These mountain-valley intensity relationships are at variance with findings of BRANCATO [1942] in a study of thunderstorm rains in the Sevier River basin of Utah. He states, "three to four times as many thunderstorms occurred on the middle and upper windward slopes of the mountains as on the relatively flat and lower portions of the basin. However, contrary to published and popular accounts, the thunderstorms produced the greatest amount of precipitation at the lower elevations and not on the mountain slopes. The most favorable condition for the production of heavy rain is the presence of an air mass with a sufficient amount of available energy and the greatest possible amount of moisture. Orographic lifting is very effective as a mechanism to release the latent energy in an air mass but as the air is lifted over progressively higher terrain the total amount of available precipitable water above any given area becomes progressively smaller. Over the lower level areas therefore there is always more potential rain waiting to be released, but the opportunity for realization occurs less frequently than at the higher elevations which are favored by orographic lifting . . .

"With regard to variation of thunderstorm rainfall with elevation, the records cited as well as records over other portions of the country show that although sloping terrain will increase the frequency of thunderstorms, the amount of precipitable water in the atmosphere above a unit area decreases with elevation, so that over a long period of time a station located at a lower elevation is likely to experience the most intense thunderstorm."

DORROH [1946] states that "data collected thus far concerning precipitation and runoff in the southwest materially substantiates this (Brancato's) hypothesis, although it must be realized that exceptions can be found." The higher mountain rainfall intensities reported in this paper seem to be one of the exceptions suggested by Dorroh.

The problem needs further study over a longer period of time.

References

- BAILEY, R. W.; CRADDOCK, G. W.; and CROFT, A. R., Watershed management for summer flood control in Utah, U. S. Dept. Agr. Misc. Pub. 639, 1947.
BAILEY, R. W.; FORSLING, C. L.; and BECRAFT, R., Floods and accelerated erosion in northern Utah, U. S. Dept. Agr. Misc. Pub. 196, 1934.
BRANCATO, G. N., The meteorological behavior and characteristics of thunderstorms, U. S. Dept. of Comm., Weather Bureau, Washington, D. C., unnumbered processed pub., 1942.
CANNON, S. Q., Chairman, Torrential floods in northern Utah, 1930. Report of Special Flood Commission, Utah Agr. Expt. Sta. Cir. 92, 1931.
DORROH, J. H., Jr., Certain hydrologic and climatic characteristics of the Southwest, Univ. of New Mexico Pub. 1, 1946.
PAUL, J. H., and BAKER, F. S., The floods of 1923 in northern Utah, Utah Univ. Bull. 15, no. 3, 1923.

Intermountain Forest and Range Experiment Station,
U. S. Forest Service,
Ogden, Utah

(Manuscript received May 13, 1949; presented at the Twenty-Fourth Regional Meeting, Denver, Colorado, April 27, 1949; open for formal discussion until July 1, 1950.)

DISCUSSION

J. H. Dorroh, Jr. (Soil Conservation Service, Albuquerque, New Mexico).--The authors have presented a very interesting and instructive paper concerning a subject that has been in much need of research in the West. Fortunately, since the establishment of the hydrologic network early in the 1940's, an increasing number of intensity data are becoming available, and it is earnestly hoped that continued studies will be made of the precipitation characteristics not only of the area covered by this paper but of the entire Rocky Mountain region. It is becoming increasingly evident that this subject is so complex that at times almost "pin point" investigations must be made before rainfall characteristics of any location may be outlined with any degree of accuracy.

During the past ten years the Soil Conservation Service has made extensive efforts to collect

and analyze recording raingage records in Utah, Colorado, New Mexico, and Arizona. This has resulted in an accumulation of significant rains from more than 1500 station years of recording raingage records. Although the types of analyses that might be made of these data are multitudinous, there have been some that followed lines similar to those discussed in this paper and which might be worth mentioning.

One interesting conclusion that can be drawn from the authors' discussion, and which is in good agreement with our studies, is the very short duration and limited quantities of thunderstorm rainfall characteristic of this part of Utah. In the University of New Mexico publication cited by the authors, considerable attention is given to intensity and duration characteristics of the four states mentioned heretofore, as they are influenced by the locations of given areas with respect to sources and normal directional movements of moist air masses. One definite conclusion reached was that northern Utah was so far removed from the source of summer moisture (Gulf of Mexico) that characteristically only enough moisture is available to permit the maintenance of high intensity rainfall for very short periods of time. It is interesting to note that of the 153 July-August rains at the Parrish station, the greatest total fall was 1.26 inches, and only three rains exceeded one inch. On the other hand, 143 or 93 per cent of these rains, totaled less than 0.50 inch. These data certainly point up the characteristically short duration of intensive rainfall; in fact, the authors state that "in most cases, the great bulk of the burst rainfall occurred in 30 minutes."

It is interesting to note, however, that toward Arizona the rainfall expectancies rise. Although the difference is much less marked in terms of short time intensities, thunderstorms are apparently able to maintain significant intensities for a greater length of time and the total amount of significant storm rainfall is more. For example, our frequency studies indicate that for a somewhat comparable frequency of, say, once in ten years, we might expect about 1.45 inches of storm rainfall at Modena, Utah, and 1.80 inches at Tucson, Arizona. Both of these stations are in the path of incoming moist Gulf air.

The foregoing statements may serve to explain in part the apparent discrepancies between the authors' study and those made by Brancato and ourselves. It is believed that in fact no real discrepancy exists, and that actually we and the authors are thinking in quite different terms. Other reasons may be given as to why we feel that the results of the authors' study are not necessarily in conflict with our statements concerning low intensity rainfall at higher elevations. These are:

First, it is more than probable that the location of this particular area, with respect to incoming moist air - and its abruptly rising topography - results in storms approaching those we have referred to as the "lift convective" type. These storms are becoming notorious as a source of high intensity rainfall.

Second, it is not likely that the available moisture at locations adjacent to but immediately below abrupt changes in topography will be much less, if any, than those up the slope. The diminution of moisture in an air mass requires the passage of that mass over a substantial section of terrain.

Third, in our studies we have given primary attention only to thunderstorms of high intensity and with sufficient duration of high intensity to result in flood flows of damaging magnitude. We have seldom been concerned with rainfall intensities as they occur over a period of less than 30 minutes, and more often than not, are primarily interested in one-hour totals. Our work, therefore, has not included the consideration of rainfall intensities occurring in periods as short as five minutes. Since intensity characteristics for five-minute intervals may bear no similarity to those for 30- or 60-minute intervals, it is quite difficult to relate our studies to that of the authors. It is noted that in Brancato's publication he refers to 1.00-inch and 1.50-inch rains, and uses Modena, Utah, as an example. This would indicate that he has been thinking in terms similar to those of the Soil Conservation Service.

The last point which may serve to clear up this apparent discrepancy is that commonly we have considered the "higher elevations" to include those areas of the Rocky Mountain region whose lower limits were at the elevations of stations used in the authors' study. In addition, of course, we have been referring only to those areas not subject to the so-called "lift convective" storms. Records from the station at Alpine, Utah, at an elevation of 10,000 ft, and behind the frontal range, are apparently typical of such areas. During 22 years of record now at hand, the greatest amount of rainfall recorded at this station in one hour was 1.10 inches. This may be compared with Modena, Utah, where, during the same 22 years, one rain totaling 1.76 inches in one hour and two additional rains of 1.30 inches were recorded. It is interesting to note that three years after this 22-year period another rain totaling 1.78 inches in one hour was recorded at Modena. We have no current data for Alpine. Peculiarly, even the five-minute intensities at Alpine appear to be low. For example, the

highest rate of rainfall recorded during the 22-year period was 2.76 in/hr for five minutes, or 0.23 inch.

The scarcity of recording raingages at higher elevations is certainly a well-known fact. In view of the meager data available, it is very difficult to state positively that intensive storm rainfall at such elevations is characteristically less than elsewhere and certainly there must be exceptions. In reviewing records from stations such as Alpine, Utah, Wagon Wheel Gap, and Leadville, Colorado, however, the absence of rainfall of high intensity and considerable duration is quite impressive.

It is hoped that this subject, as well as many others worthy of attention, will be given further study in the not too distant future. Certainly such work is greatly needed in the West.

EROSION PAVEMENT, ITS FORMATION AND SIGNIFICANCE

W. C. Lowdermilk and H. L. Sundling

(A contribution of the California Forest Experiment Station, Branch of Research,
United States Forest Service)

Introduction--Erosion pavement is a relatively new term to which experimental studies in erosion have given rise. The phenomenon is not new. It may properly be said, however, to be caused by the activities of man and his agencies in removing natural mantles of vegetation, which prior to such activity had clothed the landscapes in question. Erosion pavement is the accumulation of fragments of rock at the surface of a soil, caused primarily by the removal of the fine material by surface rain wash or wind. Such a layer of rock fragments is often conspicuous in old sloping fields and in overgrazed areas in soils containing rock fragments. Thus erosion pavement does not occur in loessal or alluvial soils of uniformly fine texture, where rilling and gullyng are characteristic.

Origin of the term, erosion pavement--In 1925 the senior author was impressed by the accumulation of rock fragments at the surface in areas where experimental studies on runoff and erosion were being conducted in the province of Shansi, China [LOWDERMILK, 1926]. At that time it was thought such accumulations, then designated as "residual rock fragments", might be used as a measure of losses of soil due to sheet erosion. By sampling uneroded soil profiles near by, it was possible to determine the amount of rock fragments in layers of various thicknesses. It was assumed that the accumulation of rock fragments at the surface represented a layer of soil similar in depth to a layer of uneroded soil found to contain a like amount of rock fragments. While this cannot be an exact measure, it is believed to be a significant one.

Further studies at Berkeley in 1927 and 1928 on the influence of forest litter on surficial runoff and erosion disclosed the interesting operation of an accumulation of rock fragments on experimental-tank soil surfaces [LOWDERMILK, 1929]. It was noted that, as artificial rain was applied successively in increasing intensities, the amount of eroded material from the Alken [STORIE and TRUSELL, 1927] and Sierra Soil Series actually diminished in total quantity. This result indicated that the sediment factor of the runoff was diminishing at an even greater rate. Repeated examination of the bare soil surfaces disclosed the formation of an accumulation of rock fragments, which apparently caused the reduction in rates of erosion. Consequently the phenomenon became of enough importance to deserve a descriptive name. During a conference concerning this phenomenon, C. F. Shaw suggested the apt term of erosion pavement for this concept.

Erosion pavement was chosen owing to its similarity in formation and character to desert pavement. The term was subsequently described and first published by SHAW [1929]. Sufficient differences between the two phenomena exist, moreover, to warrant a distinctive term. It would scarcely seem appropriate to employ the sinister implication of desert pavement to an accumulation of rock fragments on a field under humid climate; notwithstanding the fact, that so doing would have a certain justification. Desert pavement is a response to an arid climate, supporting an incomplete and interrupted cover of vegetation, whereas erosion pavement is a response to the exposure of soils containing rock fragments to the forces of erosion against which they were formerly protected by a complete mantle of vegetation.

Erosion pavement is a conspicuous phenomenon in regions where erosion has been accelerated beyond geologic norms. The smelter fume area in northern California furnishes an excellent example of erosion pavement over thousands of acres. Overgrazed ranges in the West and Southwest also exhibit the phenomenon on an extensive scale.

Experimental evidence--It is primarily the object of this paper to report briefly on the experimental evidence of the formation of erosion pavement which comes as a by-product of another study. This study was carried out at Berkeley by the California Forest Experiment Station and had for its object to measure the influence of certain ranges of gradients on surficial runoff and erosion. Experimental runs on a sandy clay loam type of the Alken soil series have been completed and form the basis for the data here presented.



Fig. 1--A general view of the lysimeter installations fitted to apply artificial rain up to intensities of four inches per hour continuously; each lysimeter is fitted with two rain troughs to measure rainfall catch, with a sediment trap and runoff collector tank as well as with a seepage collector tank; each collector tank is equipped with graduated glass gages from which readings are made systematically; the five lysimeters in the middle distance are employed in special studies on inception processes of erosion

The experimental installation has been described elsewhere; main features only will be indicated here. Each of the five lysimeters has a projectional area of 20 sq ft (34×84 inches) and was filled with three feet of soil in thin layers according to natural order. Rain troughs are placed on each side the full length of the lysimeters. These troughs discharge into collector cans fitted with graduated glass gages to facilitate direct readings of catches of rain. A baffle trough is located at the lower end of the tank at the soil surface to collect runoff and eroded material. Runoff is then conducted through a silt trap which elutriates all sediments of larger dimensions than the clay fraction. Thence the runoff is discharged into collector tanks which are likewise provided with graduated glass gages for direct readings. The percolate is allowed to collect in an inch layer of sand in the bottom of the lysimeter and to discharge directly into percolate collector cans similarly fitted for direct readings (see Fig. 1).

Provision is made for applying artificial rain in addition to natural rains by shooting 80 jets of hydrant water 20 ft into the air from two lines of pipe so as to fall back in drops over the entire installation. The simulation of rain was satisfactory. Intensities of artificial rain up to four inches an hour may be applied continuously for experimental purposes.

Table 1--Gradients of lysimeters and soil surfaces

Lysimeter	Gradient		
	Tank	Soil surface ^a	
		Before resurfacing	After resurfacing
	pct	pct	pct
1	5	6.26	6.53
2	10	13.17	11.49
3	10	13.16	11.33
4	15	18.38	17.30
5	20	22.98	22.26

^aThe soil surface was given a steeper slope than the lysimeter to allow for degradation by erosion.

The lysimeter surfaces were set at different slopes as indicated in Table 1. Lysimeters 2 and 3 were set at ten per cent as duplicates to discover experimental variations to be expected in the data.

Experimental runs-- The experimental runs are summarized in Table 2. Figures 2 and 3 show the surface of one of the lysimeters after 44 runs.

Experimental results-- A summary of the runoff data is set forth in Table 3. It is to be noted that for the artificial rains which maintained a fairly uniform intensity for the durations of application, there is a remarkable similarity in percentages of runoff for all gradients. This was an unexpected result. As may be noted in the last column of Table 3, the maximum rate of percolation for the bare soil of the five lysimeters approximated 0.70 in./hr.

The figure of 0.61 inch for lysimeter 1 reflects less uniform application owing to gusty winds from that side of the installation. Thus it appears that, when percolation capacity of this soil under other-



Fig. 2--View of lysimeter 4 showing the erosion pavement surface after 44 runs of artificial rain



Fig. 3--Details of a small area of the lysimeter shown in Figure 2; the soil surface shows the compacted and crusted condition due to the filling of interstices with fines filtered from a muddy suspension as it partially percolates into the soil; a thin layer of fine textured material is produced at the surface which determines the rate of percolation for the entire soil profile

Table 2--Experimental runs by series

Series	Duration of each run min	Number of runs in the series	Type of rain
A	30	2	Artificial (preliminary)
B	60	3	Natural
C	Irregular	6	Natural
D	Irregular	6	Natural
E	120	6	Artificial
F	15	6	Artificial
G	10	11	Artificial
H	30	5	Artificial
I	60	6	Artificial
J	120	5	Artificial
Total		56	

Table 3--Summary of runoff under artificial rain

Lysimeter	Gradients		Average intensity in/hr	Percent pct	Indicated evapo- percolation rate in/hr
	Before resurfacing	After resurfacing			
	pct	pct			
1	8.26	6.53	1.66	63.0	0.614
2	13.17	11.49	2.15	67.6	0.696
3	13.16	11.33	2.20	67.6	0.713
4	18.38	17.30	2.26	66.6	0.750
5	22.98	22.36	2.06	63.7	0.748
Average			2.07	65.6	0.704

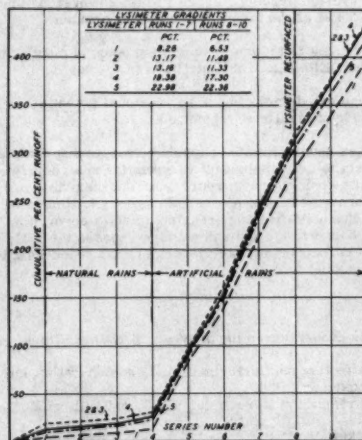


Fig. 4--Cumulated per cent of runoff for ten runs

wise similar conditions was exceeded, the gradients of these lysimeters had no significant influence on the rate of runoff (see Fig. 4).

The case was not the same for the amount of eroded material carried into the silt traps by surficial runoff. Amounts varied directly as the gradient within the range of six to 23 per cent. This is apparent on Figure 5.

The significant fact, however, was that this rate of erosion was not maintained throughout the experiment. As the runs proceeded less material was eroded. A sort of equilibrium was first established on the steepest gradient, and lastly on the flattest gradient. In time the rates of erosion from all gradients approximated each other, as the slope of the cumulative graphs in Figure 4 signify.

It was further noted that an erosion pavement had developed on all soil surfaces of this, the Alken series, which apparently accounted for this remarkable result. Thereupon the lysimeters were resurfaced to remove all vestiges of the first erosion pavement. The rate of erosion increased many fold at first, and diminished as the formation of a second erosion pavement took place.

Accordingly, analyses were made of the eroded material for comparison with analyses of the original soil. A special analysis in addition to the complete mechanical analysis to include larger rock fragments was made. Analyses were made to determine the proportions of soil particles of diameters of (1) less than two millimeters; (2) between two and three millimeters; (3) between three and five millimeters; and (4) over five millimeters.

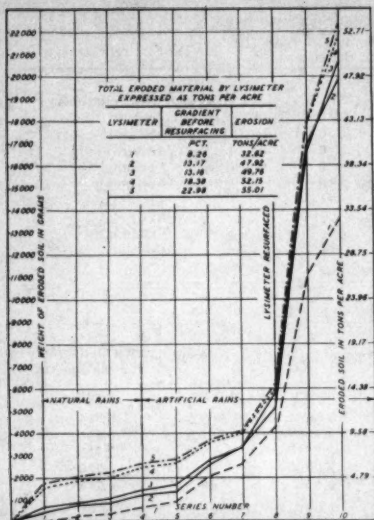


Fig. 5--Cumulative weights of eroded material for ten runs

Significance of erosion pavement--Erosion pavement is an unmistakable evidence of accelerated erosion which has been described elsewhere by LOWDERMILK [1931, p. 108] as follows:

It (accelerated erosion) represents the augmented operation of an erosional potential caused by the removal of the control exercised by a mantle of vegetation.

The control of a mantle of vegetation establishes under climates capable of supporting complete cover, a geologic norm of erosion for the given condition. This concept is essential to a comprehension of the significance of accelerated erosion. A geologic norm represents the inevitable processes of degradation and planation of land forms above sea level measured in geologic time units. A concept of the norm may be observed in natural channels draining areas completely covered by natural vegetation. The destruction of the vegetative control at the soil surface exposes the soil, which is a product of long interdependence between vegetation and soil developmental processes, to forces of erosion against which it was formerly protected.

References

- LOWDERMILK, W. C., Forest destruction and slope denudation in the province of Shansi, China, China J., v. 4, no. 3, 1926.
 LOWDERMILK, W. C., Further studies of factors affecting surficial runoff and erosion, Proc. Int. Congress of Forestry Experiment Stations, Stockholm, 1929.
 LOWDERMILK, W. C., Studies of the role of forest vegetation in surficial runoff and soil erosion, J. Agr. Eng., v. 12, no. 4, 1931.
 SHAW, C. F., Erosion pavement, Geogr. Rev., pp. 638-641, 1929.
 STORIE, R. EARL, and TRUSSELL, D. F., Soil survey of the Placerville area, California Series, no. 34, U. S. D. A. Bureau of Chemistry and Soils, 1927.

1620 LeRoy Avenue (W. C. L.),
 Berkeley 9, California

United States Forest Service (H. L. S.),
 Duluth, Minnesota

(Communicated manuscript received March 25, 1949;
 open for formal discussion until July 1, 1950.)

Table 4--Analysis of original soil and of eroded material.

Soil source	Size			
	<2 mm	2-3 mm	3-5 mm	>5 mm
	pct	pct	pct	pct
Original soil	82.6	6.4	5.8	5.2
Lysimeter 1	90.7	6.4	2.7	0.2
Lysimeter 2	89.4	6.7	6.4	0.5
Lysimeter 3	89.0	6.8	3.7	0.5
Lysimeter 4	89.6	6.1	3.8	0.5
Lysimeter 5	89.5	6.5	3.5	0.5

The results of these analyses are shown in Table 4. By comparison, the proportion of fine textured material predominated in the eroded material, whereas a very small fraction of the fragments over five millimeters in diameter were removed. The fine material was removed in greater abundance than the pebbles and fragments, which accounts experimentally for the accumulation of the rock fragments or the formation of an erosion pavement.

These reported results apply to the inception of processes of erosion. Where slopes are long enough to produce the accumulation of surficial runoff, streamlets competent to transport the larger rock fragments, form gullies whereby the erosion pavement is undermined and accelerated erosion proceeds apace. This, however, is another phase of the complex process of erosion.

RECENT APPLICATIONS OF GEOPHYSICAL METHODS TO THE STUDY
OF THE CANADIAN SHIELD

J. Tuzo Wilson

Abstract--Since the War there has been a great increase in work devoted to determining the structure of the Canadian Shield. In this paper recent studies by nine geophysical methods are described and placed in their proper geological setting.

Some of these methods, especially those employing gravimeters, airborne magnetometers and radioactive age determinations are already in widespread use. Of others much less is known. These include seismic and thermal measurements upon the shield, studies of the distribution of radioactive elements and of isotope ratios of elements, measurements of temperatures and pressures at which minerals were deposited from which depths of erosion may be deduced. A brief outline of some mathematical theories concerning the mechanism of Earth failure has been included.

The paper is primarily devoted to describing methods, not results, but it is mentioned that the present evidence is compatible with the view that the continent has grown by the accretion of roots of marginal mountain ranges. It is suggested that a better understanding of the nature of the shield can be expected soon when the new methods have been more widely applied and when the results have been more fully tested and published.

Introduction

In his Presidential Address to this Union ADAMS [1947] recently described six fundamental and unsolved problems of geophysics. He linked together the first two which he chose by stating that one might think of the problem of the origin of geosynclines and the problem of the origin of mountain-building as aspects of one really fundamental problem, the formation of continents and ocean basins.

The study of continents, if pursued to sufficiently great depths in the Earth or far enough back in time, leads to the study of the Pre-Cambrian basement. These rocks are nowhere better exposed than in the Canadian Shield. Their nature is of much interest to American geologists, as well as to Canadian, for they provide the best indication of the probable constitution of the basement underlying much of the United States. This paper briefly reviews some results obtained by applying several geophysical methods to the study of the shield, and suggests some conclusions that may be tentatively drawn.

Because rocks of Archean type crop out over relatively small areas in the United States, but form the bedrock of about half of Canada it will be well to emphasize how much the geology of different regions varies and how different is the extent of our knowledge of various parts of the Earth. In each region the local geology naturally exercises a strong influence upon the thinking and interpretations made of the regions by the geologists.

Fundamentally, there is the distinction between ocean basins and continents. Concerning the ocean basins there has been all too little geological information, but new techniques now being rapidly applied promise much more knowledge in the near future.

On the continents three types of ground show marked contrasts. These are exposed shields, areas of covered shield and those mountainous and unstable regions which BUCHER [1933] has called the mobile belts and which often form the boundaries between continents and oceans, whether they appear as young continental mountain ranges or as chains of island arcs.

The mobile belts--In the mobile belts active field work and new geophysical measurements are providing fresh data bearing upon their surface history and upon the nature of their roots. Geologists working in those regions and especially on island arcs have been impressed by the instability, seismicity, and vulcanism of these regions. Many of them believe in the existence of great convection currents flowing within the Earth's mantle, although they have not yet explained the nature of these currents in all three dimensions, neither have they indicated why the shield areas have remained

stable while convection has been proceeding in adjoining regions [UMBROGROVE, 1947].

The covered shields-- Of the shield areas, the greater parts are blanketed by relatively thin and comparatively little disturbed layers of sedimentary rocks. It is upon these covered parts of shields that a large proportion of all geological investigation has been carried out. These regions are almost without volcanoes. They have few earthquakes. Since Cambrian time, or earlier, large parts of them have been affected by epeirogenic movements only. Because the true nature of the basement rocks is hidden, or inadequately understood from small exposures, it is not surprising that many theories concerning geological processes emphasize the permanence and stability of the hidden continental platforms. Opinions have differed as to whether these platforms have remained fixed or have moved as great blocks. In any case, no explanation has yet been generally agreed upon concerning the origin of these platforms, the reason for their present distribution or the cause of their supposed migrations.

Since the surface rocks are (commonly) sedimentary strata either flat-lying or gently folded, and since the largest basic intrusives in the covered shield areas, the lopoliths, are also horizontally layered, it is natural for geologists in these regions to be predisposed to thinking of the Earth's crust as a succession of parallel horizontal shells.

The exposed shields-- These are predominantly composed of Archean type rocks whose constitution and structure forms a profound contrast to the beds which overlie them. They are largely gneisses and schists showing every evidence of past movement, flow, and igneous activity. Their dips are commonly steep and their orientation and composition change rapidly from place to place. This arrangement and gravity anomalies in these regions suggest that this heterogeneity extends to considerable depths.

Like their covered portions the shields are now stable and without volcanoes or major earthquakes, but the striking evidence of former activity suggests that once they may have passed through a stage like that now represented by the mobile belts.

Of the major Pre-Cambrian areas, several are largely hidden by ice sheets, deserts, or tropical soil, but the small Fennoscandian Shield and the large Canadian Shield are well exposed by recent glaciation. SEDERHOLM [1910] suggested the Finnish Pre-Cambrian represented the roots of ancient mountain ranges. Recently HOLMES [1948a] outlined the location of some former mountain ranges in the African Shield.

The idea that the Canadian Shield is also composed of mountain roots has often been expressed, but the location of these ranges has not been agreed upon. This is not surprising if one considers the difficulties of Pre-Cambrian geology and the fact that most mapping has been for immediate economic purposes and not directed at finding the roots of past mountains. At the present time there is hope, however, that a combination of geological knowledge and geophysical methods can shortly provide a clearer understanding of the principal structures.

The study of the Canadian Shield by field geology

It is not the object of this paper to discuss geological field work, but its achievements must be mentioned because it is obvious that by far the greatest part of our present knowledge of the Shield has been obtained in that manner. Much more effort has been applied to geological than to geophysical work. But it is not bulk that makes geological information important. The geophysical methods described below do not stand alone. To be properly applied and interpreted, they must be correlated with one another and with as much geological information as can be obtained. There is no evidence that any geophysical methods yet devised give exactly the same information or as much information as field study of the rocks. Also, serious errors in interpreting physical information may be made unless full weight be given to the probable geological nature of the rocks. A very obvious example would be any attempt to interpret observations upon heterogeneous Archean rocks in terms of horizontally layered structures such as are common in younger beds. The geological nature of the shield must therefore be considered with the ways in which geophysical methods can best be applied to supplement our knowledge of it.

By good fortune, the present state of knowledge of the Shield has recently been reviewed both by the GEOLOGICAL SURVEY OF CANADA [1945 and 1947] and by the CANADIAN INSTITUTE OF MINING AND METALLURGY [1948]. Geological maps for each province either on a scale of 12 or on 20 miles to one inch have recently been issued.

To emphasize structure, the Geological Survey of Canada and the Geological Society of America

are assisting the Geological Association of Canada in the preparation of a tectonic map of Canada which is to be a companion sheet to that prepared for the United States by the American Association of Petroleum Geologists.

These results were obtained by geological methods alone, and the difficulties of Pre-Cambrian geology described below indicate the magnitude of the achievement which these papers and maps represent.

It is apparent from some of these papers and maps that Canadian geologists consider that the Shield may be divided into provinces, although the number, boundaries, and relations between provinces are not yet well defined or agreed upon (Fig. 1). These provinces are characterized by different rock assemblages. Striking examples are the Superior (Keewatin) and Yellowknife provinces which have much basic lava of Keewatin type and little or no limestone. Some geologists consider that these provinces as far as they are known have their own distinct patterns of foliation and faulting and are characterized by igneous rocks of a common range in age and that each is an eroded orogenic belt. Among papers which distinguish provinces issued prior to these summaries are those by ELLSWORTH [1932], NORMAN [1936 and 1940], M. E. WILSON [1941], and COOKE [1947], while more recent ones are those by COOKE [1948], HENDERSON [1948], JOLLIFFE [1948], and GILL [1948 and in press]. In the summer of 1948 it was found that HOLMES [1946 and 1948a],

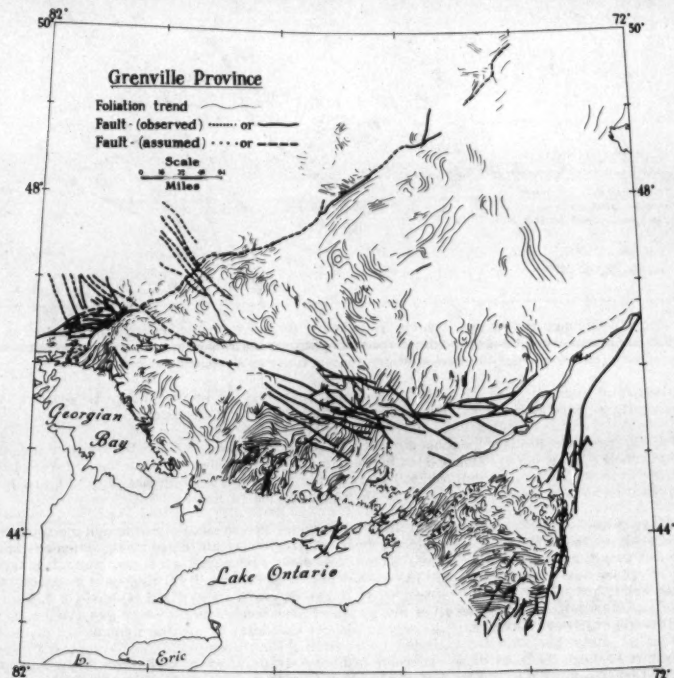


Fig. 1.--Known and assumed faults and directions of foliation in western part of the Grenville province; data for the Adirondack region from A. F. Buddington

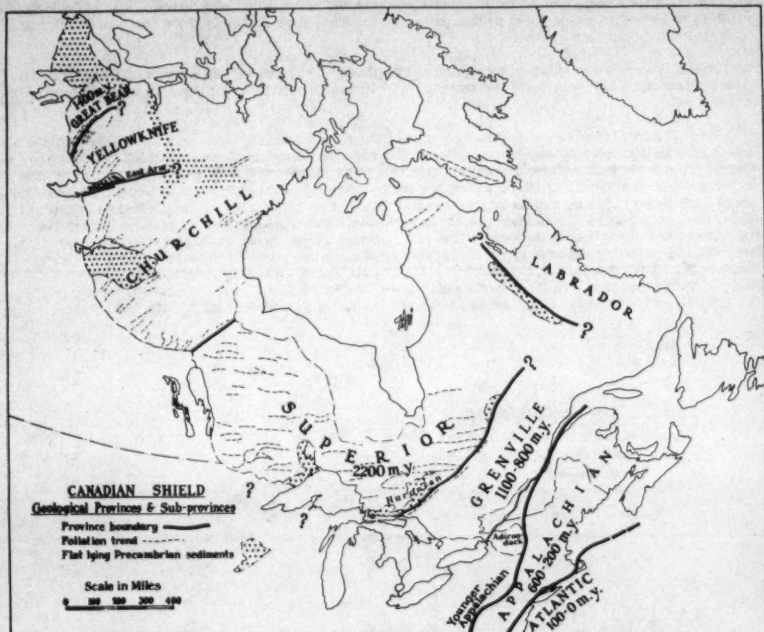


Fig. 2--Geological provinces which are possibly former orogenic belts in the Shield; each is marked by a coordinated foliation pattern; the range of age determinations considered to show the period of orogenic activity is shown where known

GILL [1948 and in press], and the writer J. T. WILSON [1949a] had by compiling earlier work, all independently arrived at similar interpretations of the structure of the Shield.

Two figures from the last mentioned paper are reproduced here to illustrate some of the points just mentioned (Fig. 1 and 2). Boundaries between rock types in general follow the patterns of foliation. The wide distribution of well foliated rocks in the shield is worth emphasizing. Figure 3 shows the structure of Grenville gneisses in an unusually clear manner.

These papers provide a geological setting to which the geophysical methods may be applied, but the view would not be complete without indicating the peculiar difficulties with which one must contend in Pre-Cambrian geology. The observations made during geological mapping fall into four classes. These are (1) studies of past life in the rocks (paleontology), (2) composition (petrology and geochemistry), (3) orientation (stratigraphy and structural geology), and (4) mode of deposition or intrusion. In most young rocks all of these aids are applicable. In the older Pre-Cambrian rocks the first aid does not appear; the second has been modified by metamorphism; and the meaning of the third may be lost. For example, Leith, writing for the United States Geological Survey, had defined Archean rocks as those "in which ordinary stratigraphic methods are not applicable" [LEITH, LUND, and LEITH, 1935]. For the fourth it is not always possible to interpret the mode of origin of highly metamorphosed rocks, nor is one sure that conditions then were similar to those of today. The field geologist is thus greatly handicapped. In addition, travel is arduous in the unsettled regions of Pre-Cambrian shields, so that, by the most liberal estimate only about one quarter of the Canadian Shield has even been traversed.



Fig 3--Foliation in Grenville gneisses south-east of Sudbury, Ontario; the large body of water in the lower right hand corner is the Middle West Bay of Lake Nipissing; area of mosaic $5 \times 4 \frac{1}{4}$ miles

Pre-Cambrian rocks extend back to the beginning of geological time and into the inaccessible depths of the Earth. Thus, there is great scope for geophysical techniques if they can assist in overcoming these manifold obstacles that face the Pre-Cambrian geologist. Nine geophysical methods are described below. The study of air photographs is also of great assistance. These are usually examined in conjunction with field work [for example, JOLLIFFE, 1942; and HARRISON, 1948], but preliminary studies can be made using air photographs alone [LANG, BOSTOCK and FORTIER, 1947; BOSTOCK, 1948; and J. T. WILSON, 1948].

The application of geophysical methods to the study of the Canadian Shield

The methods chosen for description are:

- (1) gravimeter surveys, (2) airborne magnetometer surveys, (3) radioactive age determinations, (4) mathematical approach to theories of Earth mechanism, (5) seismic measurements of crustal layers, (6) geothermal measurements, (7) studies of the distribution of radioactivity, (8) measurements of the temperature and pressure of deposition of minerals, and (9) variation of isotopic content of elements.

Others have been suggested and more are likely to be discovered or developed, but the above list includes those of the greatest importance today. Some, like the airborne magnetometer and gravimeter, are capable of being used to map large regions rapidly; others like age and temperature determinations can only be applied at specific localities although the results may have a regional significance. Some have been known for many years, whereas the last two have been applied only very recently. The application of all is being tremendously accelerated at the present time. Several of the studies are being made by the Canadian Government, some by universities with government support, while exploration companies are trying similar procedures over favorable prospecting areas on an intensive scale. Little information is available about these latter activities.

Gravimeter surveys and isostasy--Before the War, knowledge of the variation of gravity in Canada was confined to a few hundred-pendulum and torsion balance observations which had been carefully made by the Dominion Observatory. The former had been compared with values at other national base stations. [MILLER, 1931-1940].

The development of the gravimeter and its use in prospecting for oil completely altered that situation. Since 1943 regional surveys with stations along roads at intervals of a few miles or less have been made by the Dominion Observatory for the greater part of the Prairies, the St. Lawrence Valley, and the Maritime provinces. To these are now being added the values obtained for a selection of the great number of stations measured by oil companies. These regional surveys have been extended into the Shield along most of the roads penetrating into mining districts, and hundreds of additional stations have been obtained by landing on lakes at about 20-mile intervals in a broad network extending from Great Slave Lake around the southern edge of the Shield into Quebec [MILLER, 1946 and 1947; ANONYMOUS, 1948 and 1949].

The Dominion Observatory proposes to publish more of these data shortly and one paper interpreting the structures in northern Ontario in terms of gravity measurements has already been prepared [GARLAND, 1947 and in press].

Gravity data from the Canadian Shield can be expected to throw interesting light upon the degree to which isostatic equilibrium is maintained in this area. The Shield is an old and stable area, which has long been without high mountain ranges. It might be expected to be in fair isostatic

equilibrium except to the extent that it was weighted down by the Pleistocene ice sheets and has not recovered.

Most geologists agree that it was depressed by the ice and that widespread raised beaches hundreds of feet above sea level indicate that it has partially recovered from that loading. Opinions differ upon whether the uplifting is still in progress and whether it can be expected to proceed farther.

The information pertinent of this problem in the past was extremely fragmentary and is still not adequate to arrive at its complete solution, but is nevertheless of interest. The idea that the land around Hudson Bay is now rising was supported by the undoubted fact that the land had recently risen, and by the view held in Scandinavia, where supposedly analogous conditions exist, that the land there is rising. GUTENBERG [1941] established that the Great Lakes are being tilted so that the water is getting shallower in the northern parts and deeper in the southern. He interpreted inadequate tidal data, that were available from Churchill, to show that the land there was rising relative to sea level at least three feet and perhaps six feet or more a century. This was a very reasonable interpretation of the only information available. WOOLLARD [1949] felt that that interpretation was strengthened by the measurement of large negative Bouguer gravity anomalies north of Lake Superior, which theory had predicted. He pointed out that if certain assumptions were true the region would have to rise about another 4000 ft to be in isostatic equilibrium.

Many Canadian geologists have long held contrary views. TYRRELL [1896a and b], JOHNSTON [1939], COOKE [1942], and WILLIAMS [1949] have held that there is no evidence that the land is rising rapidly at Churchill today and accurate records from an official tide gage installed at Churchill in 1940 bears them out. The land is not rising rapidly. It may even be sinking slowly. MOORE [1948] has recently suggested that Gutenberg's views on the direction of tilting of the Great Lakes were correct, but that the tilt has been brought about by the southern part of the lakes sinking relative to sea level more than by the northern part rising as Gutenberg supposed. His data show that the hinge line of zero movement approximately follows the edge of the Shield, and may be more closely connected with the Shield than with former ice sheets.

Recent gravity work by the Dominion Observatory staff [GARLAND, 1947 and in press] has shown large changes over short distances in the value of gravity anomalies over the Shield in northern Ontario. Garland has interpreted these to be caused by large differences in the thickness of the granitic layer of the Shield. These differences in thickness may be as great as ten kilometers.

Woollard has pointed out that MILLER [1948] found large negative anomalies in Nova Scotia associated with granite batholiths. A similar effect may occur in the Shield. If the average of Bouguer anomalies over the Shield is negative it may be caused by the facts that there is much granite in the area and that the Shield is a stable area of old mountain roots very slowly rising around the margins if not in the center. It is presumably surrounded by sinking sedimentary basins.

As more tidal, leveling, and gravity observations are made and published this subject will be due for review. The conclusions can be expected to influence thought both on Canadian geology and on the principle of isostasy. Observations on the Shield, where the basement is exposed will have a bearing upon interpreting gravity data from other places where the effect of the basement rocks can only be speculated upon.

Several detailed studies over ore bodies, batholiths, basic intrusives, and major fault zones have also been made during the summers of 1948 and 1949 [INNIS, 1949].

It is too early to assess the value of this work adequately but gravity values undoubtedly reflect some of the largest geological structures. Readings can be obtained with an accuracy sufficient for regional studies at a rate chiefly dependent upon speed of transport between stations. This method has the advantage of providing information of the distribution of bodies with depth that it might not be possible to gain in any other way.

Airborne magnetometer surveys--The first demonstrations of airborne magnetometers in Canada were by the United States Geological Survey at request of Canadian Government and by H. Lundberg in 1946. Since then tens and perhaps hundreds of thousands of square miles have been surveyed by the Geological Survey of Canada and several commercial companies. Results are only now beginning to be published [GEOLOGICAL SURVEY OF CANADA, 1948], but the work of companies has largely been kept secret. It is therefore difficult to assess the results.

In general, it seems that the trend of Keewatin greenstone belts can be made out. Diabase

dikes, iron formations, and ultra-basic intrusives are generally conspicuous. Intrusives and contact zones rich in magnetite are discernible, but the distribution of magnetite is sometimes irregular. Examples include some gabbros, syenites and the transition zone of the Sudbury irruptive. Magnetite deposits and some massive sulphides can be distinguished. Faults show where they offset rocks with differing magnetic properties. These are general rules but interpretation is not usually easy and should be guided by as much geological information as is available. The interpretations obtained are not usually final ones but suggest places to be investigated on the ground. Disseminated magnetite is the cause of many anomalies. One great advantage of the method is that moderate cover does not hide the larger anomalies.

In spite of these limitations the airborne magnetic surveys are so rapid that it seems likely that large areas of the Shield will be surveyed in the next few years. If it is economically justifiable much structural information can be obtained by its use. This is another method which will not reduce the need for field work, but which may add much new information quickly.

Radioactive age determinations--In 1932 H. V. Ellsworth of the Geological Survey of Canada published 35 age determinations based upon chemical analyses for uranium, thorium, and lead of radioactive ores from several places in the Shield. Several of these have been checked by isotope analysis and their reliability verified. In 1941 B. Willis and R. Willis listed seven localities in the Canadian Shield in a list of 41 occurrences for which lead age determinations considered to be reliable had been made. Since then only a few more chemical analyses for this purpose are known to have been made in the Canadian Shield. A mass spectrometer built for the purpose of checking these and additional chemical analyses is now nearing completion at University of Toronto. The tube for it was made by H. C. Thode at McMaster University.

AHRENS [1949] has provided wholly independent confirmation of some of these lead age determinations using analyses for rubidium and strontium.

Age determinations by the helium method were extensively tried, but did not give satisfactory results for a long time [EVANS, GOODMAN, KEEVIL, LANE and URRY, 1939; and KEEVIL, 1941]. Work in Canada on this method has stopped, but recently HURLEY [1949 and 1950] has reported that with suitable precautions reliable results may be obtained. Early errors in age determinations by the helium method have undoubtedly delayed acceptance of all methods of radioactive age determinations.

For one Pre-Cambrian occurrence, that of pegmatites occurring in Keewatin type basic lavas in southeastern Manitoba, all three methods have been applied. They give concordant ages of about two billion years.

Since there does not appear to be any valid criticism of the accuracy of these determinations, [HOLMES, 1948b] only two questions logically prevent their complete acceptance. One point that has been raised is whether these ages do not exceed the calculated age of an apparently expanding universe. The notion that the universe is really expanding is not universally accepted. The belief that it is expanding, and calculations of the rate of expansion demand more numerous and more abstract assumptions than are involved in making determinations of the age of rocks [BONDI, 1948]. It would seem more reasonable to argue that the determined age of the Earth and of rocks probably puts a lower limit upon the possible age of the universe. Geologists were quite right in the last century in believing in the great age of the Earth when Lord Kelvin and most other physicists purported to show (knowing nothing of radioactivity) that a great age was impossible. They may be equally right in this case.

The other criticism is that, while the ages determined may be correct, the minerals and pegmatites for which the ages were obtained may be much younger than the surrounding rocks. In some cases this is undoubtedly so. For example, the Paleozoic age determined for one occurrence near Great Bear Lake is either in error or the uraninite was emplaced long after the surrounding rocks had been formed. On the other hand, there is an analogy which suggests that the older radioactive minerals in any area approach the age of the country rocks surrounding them. In any one area the determinations indicating greater age are usually the more numerous and cover a range of a few hundred million years. Each area to which such a range applies may represent a single orogenic belt.

For example, all the age determinations in the coast ranges given by WILLIS and WILLIS [1941] lie in the range 0 to 100 million years. This is the period when much deposition, folding and major intrusion occurred in that region. The greater ages given in the Rocky Mountains are due to uplifted blocks of Pre-Cambrian and lie farther inland. Likewise, the range 200 to 600 million years given by the values both of Willis and Willis and of Ahrens in the Appalachian region is contemporaneous

with much of the deposition and most of the folding and intrusion in that region. Is it not therefore plausible to suppose that the time range of similar length, 800 to 1100 million years, well established for the Grenville region, represents the time when that region was built into mountains, and that the determinations for Keewatin rocks, roughly 2000 million years, means that they are of approximately that age also?

During the past few years there has been much prospecting for radioactive minerals in the Canadian Shield and many new occurrences have been reported. Age determinations can be made from non-commercial as well as from commercial deposits. When all known deposits have been thus studied it will be interesting to see if all the determinations made in each orogenic belt which is suggested by structure give ages lying within a limited time range.

The belts become older towards the center of the Shield and suggest that the continent has grown from nuclei of which the Superior and Yellowknife provinces appear to be two. It has already been pointed out that these regions have peculiar rock assemblages, rich in lava and poor in limestone. If the continent had not grown by marginal accretion of successive mountain belts and if the shield of old eroded roots had not become stable how could one explain the peculiar distribution of ages?

Theories of Earth mechanism-- Before going farther it will be well to point out that, although each of the techniques being discussed provides some fragmentary information about the shield or the Earth as a whole, it is difficult to connect such very different types of information together. To apply these scraps of information to the best advantage a theory of the Earth's mechanism and behavior is desirable.

Most geological theories of the Earth's behavior have been built up to fit field observations. This is the way in which SUESS [1904], WEGENER [1924], BUCHER [1933], and GILLULY [1949] among others have arrived at their conclusions. Physicists have generally adopted a more analytical approach. They have considered ways in which a sphere would fall or behave if it had certain idealized properties assumed to approximate to those of the Earth. It was thus that JEFFREYS [1929] stated the contraction hypothesis, and VENING MEINESZ [1947] discussed shear patterns on the Earth's crust. In similar inductive fashion GRIGGS [1939] and VENING MEINESZ [1948] have discussed the behavior of convection currents.

Recently it was suggested that a hypothesis of LAKE [1931] might be extended to explain all the present island arcs and mountain belts [J. T. WILSON, 1949b], and that past operation of the system might explain the shields as composite roots of ancient mountain ranges as LAWSON [1932] and HOLMES [1946, p. 401-402] had suggested. Mathematical analysis by A. Scheidegger of points, selected from half a dozen arcs by the author has shown that they are not circular arcs as Lake supposed but spirals and that Lake's explanation of compressional failure in a brittle crust would not produce any pattern like that of existing ranges and arcs. Nevertheless, some of the conclusions are still sound. Further analysis by Scheidegger also makes it seem unlikely that the present surface pattern could be produced by convection currents, however inviting the two-dimensional treatment of their cross-sections may seem. He considers the most probable explanation is that slip surfaces could be produced in a plastic spherical shell (asthenosphere) by contraction and tension which would give spiral intersections with the surface of a sphere. Deep earthquakes might occur along these surfaces. The shape of arcs might be considered as controlled by these deep failures, although the details of arcs might be due to compression in the brittle crust above the level of no strain. Thus, mobile belts would have features due to both tension and compression as Bucher pointed out, although not for the reason he postulated.

These ideas are being further examined. Theories of Earth mechanism are particularly important in Pre-Cambrian geology. These oldest rocks extend to greater depths in the Earth's interior and of course further back into past time than do the younger deposits. They form the link between field observation and physical theories of the Earth's constitution and origin. Pre-Cambrian rocks are known that are two thirds of the age of the Earth [HOLMES, 1947 and 1948b], whereas Cambrian and subsequent ones were all formed within the last sixth of geological time. There is, therefore, a better chance for discovering from them if there have been orogenic pulsations in the Earth's history and if so, what have been their nature and rhythm.

Seismic measurements upon crustal layers--A knowledge of the number and nature of the layers that make up the Earth, and particularly a knowledge of the crustal layers is of fundamental importance to any theory of the nature and history of continents and ocean basins. The existence of two major discontinuities was suggested about 40 years ago. One at the boundary of the core (Weichert-Gutenberg discontinuity) has never been doubted. Another at the base of the crust (Mohorovičić discontinuity) certainly exists beneath the continents. Discontinuities at many other depths have been

suggested from time to time and others are still being suggested.

The number and variety of these proposals is very confusing. The five different interpretations of records obtained from the Helgoland explosion of April 18, 1947, made by three groups of seismologists will serve as an example. From these records MINTROP [1949] found discontinuities at 4, 13, 28, 57, 110, and 118 km depth. WILLMORE [1949] was fairly certain that there were only two certain discontinuities at 7 and 27 km, but considered there was a possibility of an alternative interpretation involving discontinuities at 8, 14, and 30 km.

From the same explosion POMERANTZ, PERKINS, ATANASOFF, and BONWIT [1948] state that the records of the P-velocities suggest discontinuities at 7.9, 18.4 and 24.8 km while the S-velocities suggest them at 7.0, 18.9, and 30.8 km. They also give other values for the surface layer of four and ten kilometers. They recognized the uncertainty of their results for they state, "It is futile to speculate on the accuracy of the present results. Additional tests or a more detailed study of the present data based on reflected or transformed waves is necessary."

All these interpretations were based upon the assumption that the Earth's crust is made up of a number of horizontal and uniform layers through which the seismic waves travel by the most direct paths. In the absence of information to the contrary and as a first approximation these were reasonable first assumptions, but they obviously have not led to conclusive results. One cannot but suspect that the true situation is more complex. Errors in the assumptions may be of several kinds. First there is considerable uncertainty and judgment involved in selecting phases from seismograph records. Second multiple reflections between layers and changes of phase at interfaces can produce results which could be interpreted as being caused by more layers than really exist. These possible sources of error are well known to seismologists. In the last section it was pointed out that the Archean basement, which is presumably the same as the granitic layer, is far from homogeneous and may vary greatly in thickness. These effects might be expected to produce scatter of points plotted on the time-travel curves so that they would not lie well on straight lines. Finally, on quite other grounds, which have not yet been controverted, STONELY [1948] has suggested that there is only one discontinuity in the crust. This is presumably the Mohorovičić discontinuity or the base of the granitic rocks. In some places there is, of course, a thin upper layer of sediments as well. Against this it must be admitted that seismologists have for many years considered that there is also one intermediate layer below the granitic layer, and strong petrological arguments in support of that view have been advanced [KENNEDY and ANDERSON, 1938; and BUDDINGTON, 1943]. In these circumstances, as Pomerantz and his colleagues pointed out, additional tests are needed to clear up the present uncertainty. At least two are in progress.

Since 1946 J. H. Hodgson has been making a study of the layers beneath the Canadian Shield for the Dominion Observatory. He is making use of rockbursts as a source of energy. The geology of the exposed basement rocks is known and local variations in velocity along the paths to observation points can be measured. A gravity survey of the whole region is being made. His initial results suggested that the crust was composed of two or perhaps three layers, [HODGSON, 1947]. Since then, he has done much further work, but he has not yet made a final interpretation, except to say that it will certainly not suggest more layers. It is hoped that definite results will be published after the summer of 1950.

Tuve and his colleagues have also been attempting to clarify this confusing situation by studying explosions in the Appalachian region using very sensitive seismographs [TUVE, 1948; and TUVE, GORANSON, GREIG, ROONEY, DOAK, and ENGLAND, 1948]. They have recorded finding discontinuities at 10, 24 and 42 km but these are only preliminary results, work is continuing and the final conclusions may be different. G. D. Garland and the writer have replotted their first results [TUVE, 1948, pp. 61-63], and consider that a single main discontinuity and granitic layer with a probable thin surface layer provides an equally satisfactory interpretation if some scatter of the points on the time-travel curve is expected and allowed for. Tuve's and Hodgson's final results can be expected to give an authoritative opinion on this matter, but as long as the possibility of drawing different conclusions from the same data remains, so does the present uncertainty about crustal layers. In the meantime, it seems possible that a widespread belief in the existence of several crustal layers tends to perpetuate itself in the absence of conclusive determinations to disprove it.

Until that proof is forthcoming it is possible to believe that besides the sedimentary rocks there is only one layer above the Mohorovičić discontinuity, a heterogeneous granitic one of varying thickness. In that case, it is easy to explain the effect of the foliated gneisses of the shield and why there are large variations in gravity anomalies over them. It is possible to believe that such rocks are largely altered sedimentary and volcanic rocks, initially laid down in sinking continental shelves with associated volcanic arcs [LAWSON, 1948]. If, on the other hand, it is satisfactorily shown that

the crust is composed of several horizontal layers, a predominantly igneous origin for shields might be favored, but the structure of Archean rocks and the gravity anomalies over them would need to be explained.

Geothermal studies--It has been supposed by many writers that the forces necessary to raise mountains are generated by the Earth acting as a heat engine. In any consideration of the behavior of the Earth it is, therefore, of fundamental importance to know whether the Earth is cooling or not. The obvious way to do that is to measure the heat flow reaching the surface and subtract from that, estimates of heat being generated by radioactivity in the rocks [JEFFREYS, 1929; and SLICHTER, 1941].

The temperature gradients in Canadian mines have long been known [CLELAND, 1933], but recently MISENER [1949] has accurately measured the rock temperatures in some hundreds of underground drill holes at many levels in eleven of the deepest mines in Ontario and Quebec. Besides these measurements, samples have been collected, whose thermal conductivity is being measured in the laboratory. An attempt has been made to check these laboratory measurements by measuring the conductivity between drill holes underground. As a result of this work, a number of accurate figures on heat flow in the Canadian Shield should soon be available to compare with similar measurements elsewhere [EVANS, GOODMAN, and KEEVIL, 1942].

The hundreds of precise measurements made underground and away from the effects of ventilation show that the isogeothermal surfaces are not level. When temperature and heat flow variations have been correlated with geology and ore distribution there are some suggestions that the interpretations may be of value to geologists and miners in practical ways not anticipated when the research was started.

Distribution of radioactivity--For the purpose of estimating the heat generated by radioactivity it is possible to measure the radioactivity of samples of the surface rocks and meteorites and try to match these samples with the various layers in the Earth. There is admittedly an element of guesswork in this, but fortunately most of the radioactivity of the Earth resides in the crustal rocks for which there is the best control. Keevil and his associates measured the radioactivity of thousands of North American rocks and expect to publish the resulting averages shortly. He and Ingham [KEEVIL, KEEVIL, INGHAM, and CROMBIE, 1943; and KEEVIL and INGHAM, in press] started to investigate the distribution of radioactivity in specific intrusives. Since 1946 that work has been carried on by SLACK [1949] and others. The average values of heat generation due to radioactivity obtained in deeply eroded Pre-Cambrian rocks are much lower than the value of 5.8×10^{-6} cal/gm/yr given for granites by BULLARD [1942]. This value in turn was lower than earlier estimates. These decreases in estimate of heat generated by radioactivity increase the chance that the Earth may be cooling by conduction.

It has also been shown that the distribution of uranium and thorium in batholiths is not haphazard but that these elements are arranged in symmetrical ways which may be of considerable geological interest. These investigations have been speeded up since Bullard, Slack, and Witham developed and built a portable instrument which can measure the radioactivity of country rocks *in situ* in a matter of minutes.

Temperature and pressure of deposition of minerals--SMITH [1947] has recently described a method of determining the temperature of deposition of pyrite. He, SCOTT [1948], and PEACH [1949] have also developed a method for determining the temperature at atmospheric pressure at which liquid inclusions present in minerals exactly fill the minute cavities in which they occur leaving no vapor phase. This establishes the particular temperature-pressure curve upon some point of which the mineral crystallized. Now if the mineral is pyrite or closely associated with pyrite the particular temperature and hence from the graph the particular pressure at which the mineral crystallized can be determined. The depth of erosion since deposition can be found from this pressure.

These developments are very new and have only been applied to the study of ore deposition on any scale during the past year, and are open to question. If they prove valid, they provide new tools applicable to a wide variety of problems especially in Pre-Cambrian rocks. [SMITH, 1948; and SMITH and PEACH, 1949]. It is possible that these methods may be developed so that measurements can be made of depths of erosion, paths of ore bearing solutions and conditions of intrusion and rates of cooling of intrusives.

Variations of isotopic content of elements--Recently UREY and others [1948] reported a method of measuring paleotemperatures of water in which fossil marine organisms lived by means of studying the isotopic abundances of oxygen obtained from the calcium carbonate of fossil shells.

At the same time, THODE, MacNAMARA, and COLLINS [1949] at McMaster University were studying natural variations in isotopic content of sulphur from various sources. Of the many samples for which the ratio of S^{32}/S^{34} was investigated, seven were from rock sulphates from various localities and 19 were for pyrite from many other localities. For all the sulphates the ratio was between 21.59 and 22.12 while all the pyrites but one lay in the range 22.00 to 22.47. Thus, the range for sulphates was distinct from that for sulphides with the exception of one pyrite sample with a value 21.61 in the lower part of the sulphate range. This sample was the only one from Franklin Furnace, N. J. Thode has discussed the geological significance of this and concluded that the fact that the S^{32}/S^{34} ratio for the Franklin, N. J. pyrite lay at the bottom of the sulphate range may mean that the iron was in the form of a sulphate at one time and later was converted to pyrite. Because it has been suggested that the Franklin deposit might be an altered sedimentary ore, this determination has particular interest, although one sample proves nothing.

In the same paper he gives isotopic abundances for two samples of pyrite in each of which the crystals grade from fine in the center to coarse on the outside. He states: "The results indicate that there is a definite variation in the isotopic abundance of the sulphur from the center out. Further, the pyrite geothermometer temperature measurements indicate a corresponding variation in crystallization temperature from the fine to the coarse crystals (in the same specimen)." This opens the possibility of extending the scope of Smith's investigations which were reported in the last section.

When the isotopic contents of more specimens have been investigated and when more of the rock-forming elements have been investigated it will be possible to draw more definite conclusions. At present, nothing is known of the variations in isotopic abundance for many of the commonest elements in rocks such as iron or silicon. In the meantime, one can agree with Thode and his associates that "Isotopic data of high precision have already made a notable contribution to chemistry and geology and promise to be very fruitful in the future."

Other physical methods--A number of other physical aids to geology may be cited. Electrical and electro-magnetic methods are already used for prospecting, and investigations at greater depths are possible. The natural neutron flux presumably causes some radioactive disintegration of certain elements. The peculiar isotopes so formed might be identified and used for measuring geologic time.

Conclusion

Of the large amount of new thought and effort now being applied to the study of the Canadian Shield, some of the geophysical methods have been reviewed. In the geophysical methods, developments have been so numerous and rapid since the War that publication has not kept pace. Of course, work by these methods constitute only a small part of the work being done in the Shield. Much of the rest is development of well tried geological procedures and much geological research is also being done [HAWLEY, 1949]. In 1948 about half the mining geophysical work in the world was carried out in Canada at an estimated cost of one million dollars [ECKHARDT, 1949]. Some methods are already widely applied and accepted. Concerning some of the others so little is known that it is now impossible to assess their value, but there is in these methods, because they are still fresh and undeveloped, the possibility of revolutionary ideas and progress. So numerous and powerful do these methods appear to be, that it is becoming recognized in Canada that the best hope of elucidating Pre-Cambrian history quickly and of finding new mines is by combining a variety of physical measurements with older geological methods. There are already grounds for hope that in this way a much clearer knowledge of Pre-Cambrian history may be obtained in a short time than would have been thought possible even a few years ago.

In the meantime, this paper has been more concerned with techniques than interpretation, because results will be much more plentiful in a few years. This paper has, however, reflected the view in which the writer [J. T. WILSON, 1949a and in press] follows the idea of LAWSON [1932] that the Earth's surface was uniform and basic at its origin. The continents perhaps originated as volcanic islands. In any case, they have grown *in situ* by the accumulation of more acid materials in shelves about the margins, the failure of these shelves [LAWSON, 1948], and the enrichment of them in acid material to form a succession of marginal mountain ranges. The eroded roots of the older ranges now form the shields.

In Pre-Cambrian geology and in geology of the ocean floors these physical methods are particularly important. Not only are other aids largely lacking, but Pre-Cambrian time constitutes that five sixths of geological history which links the younger rocks with the origin of the Earth, while Pre-Cambrian rocks form the floor which connects the younger rocks with the interior. Only by

indirect physical and chemical methods can these vastnesses be plumbed and that great knowledge of the accessible and economically important rocks which geologists have acquired be broadened to become again the science of the whole Earth.

Instead of replacing geological work, physics of the Earth should stimulate and guide it. If geology needs the help of physical aids it is even more true that the applications and interpretations of physical methods are only likely to be fruitful if based upon an accurate appraisal of geological information. Geological studies have long been based upon a sound foundation of chemistry and biology. It is now widely recognized [GEOLOGICAL SOCIETY OF AMERICA, 1946 and 1948] that the same intimate connection must be established between modern developments in physics and in geology.

The writer is grateful to his colleagues E. C. Bullard, J. H. Hodgson, A. D. Misener, A. Scheldegger, and G. D. Garland for suggestions, and to the last for reading the manuscript. His thanks are due to several branches of Department of Mines and Resources, Canada, to the Department of Geology, University of Toronto, and to A. F. Buddington and to authors of papers too numerous to mention for help in preparing this compilation. He would particularly like to acknowledge the stimulating influence of the writings of those masters of Earth science, A. Holmes, H. Jeffreys, and A. C. Lawson. Technical help was provided by Angela Burlinson, A. Aiken, and Marion Thompson.

References

- ADAMS, L. H., Some unsolved problems of geophysics, *Trans. Amer. Geophys. Union*, v. 28, pp. 673-679, 1947.
- AHRENS, L., Measuring geologic time by the strontium method, *Bull. Geol. Soc. Amer.*, v. 60, pp. 217-266, 1949.
- ANONYMOUS, Gravity work by the Dominion Observatory, *Can. Geophys. Bull.* v. 2, no. 3, pp. 47-49, 1948.
- ANONYMOUS, Gravity work by the Dominion Observatory, *Can. Geophys. Bull.*, v. 3, no. 1, p. 32, 1949.
- BONDI, H., Review of cosmology, *Mon. Not. R. Astron. Soc.*, v. 108, no. 1, pp. 104-120, 1948.
- BOSTOCK, H. S., Physiography of the Canadian Cordillera, with special reference to the area north of the Fifty-Fifth Parallel, *Geol. Surv. Canada, Mem.* 247, 1948.
- BUCHER, W. H., The deformation of the Earth's crust, Princeton, N. J., 1933.
- BUDDINGTON, A. F., Some petrological concepts and the interior of the Earth, *Amer. Min.*, v. 28, pp. 119-140, 1943.
- BULLARD, E. C., Radioactive heat generation in rocks, *Mon. Not., R. Astron. Soc., Geophys. Suppl.*, v. 5, no. 2, pp. 41-47, 1942.
- CANADIAN INSTITUTE OF MINING AND METALLURGY, Morley E. Wilson, editor, *Structural geology of Canadian ore deposits*, Montreal, 1948.
- CLELAND, R. H., Rock temperatures and some ventilation conditions in the mines of northern Ontario, *Trans. Can. Inst. Min. Metal.*, v. 36, pp. 379-407, 1933.
- COOKE, H. C., Is the land around Hudson Bay at present rising?, *Amer. J. Sci.*, v. 240, pp. 147-149, 1942.
- COOKE, H. C., *Geology and economic minerals of Canada*, *Geol. Surv. Can., Econ. Geol. Ser. no. 1* (3rd ed.), p. 20, 1947.
- COOKE, H. C., Back to Logan, *Trans. R. Soc. Canada, Sec. 4*, v. 42, pp. 29-40, 1948.
- ECKHARDT, E. A., Geophysical activity in 1948, *Geophysics*, v. 14, pp. 477-185, 1949.
- ELLSWORTH, H. V., Rare-element minerals of Canada, *Geol. Surv. Can., Econ. Geol. Ser. no. 11*, 1932.
- EVANS, R. D.; GOODMAN, C.; and KEEVIL, N. B., Radioactivity: the Earth's heat and geological age measurements, *Geol. Soc. Amer., Spec. Pap.* 36, sec. 18, 1942.
- EVANS, R. D.; GOODMAN, C.; KEEVIL, N. B.; LANE, A. C.; and URRY, W. D., Intercalibration and comparison in two laboratories of measurements incident to the determination of the geological ages of rocks, *Phys. Rev.*, v. 55, pp. 931-946, 1939.
- GARLAND, G. D., Gravity anomalies of northern Ontario (abstract), *Can. Geophys. Bull.*, v. 1, no. 4, p. 23, 1947.
- GARLAND, G. D., Gravity anomalies in northern Ontario, *Pub. Dom. Observatory*, in press.
- GEOLOGICAL SOCIETY OF AMERICA, *Interim Proc.*, pt. 1, 1946.
- GEOLOGICAL SOCIETY OF AMERICA, *Interim Proc.*, pt. 2, 1948.
- GEOLOGICAL SURVEY OF CANADA, Geological map of Dominion of Canada, 1945.
- GEOLOGICAL SURVEY OF CANADA, *Geology and economic minerals of Canada*, *Econ. Geol. Ser. no. 1*, (3rd ed.), 1947.
- GEOLOGICAL SURVEY OF CANADA, *Arnprior sheet* (1 inch to 1 mile), airborne magnetometer survey, 1948.
- GILL, J. E., Mountain building in the Canadian Pre-Cambrian shield (abstract), volumes of titles and abstracts, p. 88, *Inter. Geol. Cong.*, London, 1948.

- GILL, J. E., Mountain building in the Canadian Pre-Cambrian Shield, *Trans. R. Soc. Can., Sec. 4*, v. 43, in press.
- GILLULY, JAMES, Distribution of mountain building in geologic time, *Bull. Geol. Soc. Amer.*, v. 60, pp. 561-590, 1949.
- GRIGGS, D. T., A theory of mountain building, *Amer. J. Sci.*, v. 237, pp. 611-650, 1939.
- GUTENBERG, B., Changes in sea level, postglacial uplift, and mobility of the Earth's interior, *Bull. Geol. Soc. Amer.*, v. 52, pp. 721-771, 1941.
- HARRISON, J. M., Kissing, map 970A, *Geol. Surv. Can.*, 1948.
- HAWLEY, J. E., Current research in the geological sciences in Canada, *Canadian Min. Metal. Bull.*, v. 42, no. 445, pp. 238-443, 1949.
- HENDERSON, J. F., Extent of Proterozoic granitic intrusions in the western part of the Canadian Shield, *Trans. R. Soc., Canada, sec. 4*, v. 42, pp. 41-53, 1948.
- HODGSON, J. H., Analysis of travel times from rockbursts at Kirkland Lake, Ontario, *Bull. Seis. Soc. Amer.*, v. 37, pp. 5-17, 1947.
- HOLMES, A., The principles of physical geology, pp. 401-402, New York and London, 1946.
- HOLMES, A., The age of the Earth, *Nature*, v. 159, pp. 127-136, 1947.
- HOLMES, A., Unpublished address to Inter. Geol. Cong., London, 1948a.
- HOLMES, A., The oldest known minerals and rocks, *Trans. Edinburgh Geol. Soc.*, v. 14, pp. 176-194, 1948b.
- HURLEY, P. M., Age of Canada's principal gold-producing belts, *Science*, v. 110, no. 2845, pp. 49-50, 1949.
- HURLEY, P. M., Progress report on age measurements, *Trans. Amer. Geophys. Union*, v. 31, pp. 142-144, 1950.
- INNES, M. J. S., An investigation of the applicability of gravimetric and magnetometric methods of geophysical prospecting, *Can. Min. Metal. Bull.*, no. 448, pp. 355-361, 1949.
- JEFFREYS, H., *The Earth* (2nd ed.), Cambridge, 1929.
- JOHNSTON, W. A., Recent changes of the land relative to sea level, *Amer. J. Sci.*, v. 237, pp. 94-98, 1939.
- JOLLIFFE, A. W., Structures in the Canadian Shield, *Trans. Amer. Geophys. Union*, V. 23, pp. 699-707, 1942.
- JOLLIFFE, A. W., The northwestern part of the Canadian Shield (abstract), *Inter. Geol. Cong.*, volume of titles and abstracts, p. 93, London, 1948.
- KEEVIL, N. B., The unreliability of the helium index in geological correlation, *Univ. of Toronto Studies, Geol. Ser.* no. 46, pp. 39-67, 1941.
- KEEVIL, N. B., and INGHAM, W. H., Radioactivity and petrology of Bourlamaque and Elzevir batholiths (in press).
- KEEVIL, N. B.; KEEVIL, A. R.; INGHAM, W. N.; and CROMBIE, G. P., Causes of variation in radioactivity data, *Amer. J. Sci.*, v. 241, pp. 345-365, 1943.
- KENNEDY, W. Q., and ANDERSON, E. M., Crustal layers and the origin of magmas. *Bull. Volcanologique, Ser. 2*, Tome 3, 1938.
- LAKE, P., Island arcs and mountain building, *Geog. J.*, v. 78, pp. 149-160, 1931.
- LANG, A. H.; BOSTOCK, H. S.; and FORTIER, Y. O., Interim catalogue of the Geological Survey collections of outstanding air photographs, *Geol. Surv. Can.*, Paper 47-26, 1947.
- LAWSON, A. C., Insular arcs, foredeeps and geosynclinal seas of the Asiatic coast, *Bull. Geol. Soc. Amer.*, v. 43, pp. 353-381, 1932.
- LAWSON, A. C., Some further implications of the doctrine of isostasy, *Bull. Geol. Soc. Amer.*, v. 59, pp. 197-210, 1948.
- LEITH, C. K.; LUND, R. T.; and LEITH, A., Pre-Cambrian rocks of the Lake Superior region, p. 10, *U. S. Geol. Surv. Prof. Pap.* no. 184, 1935.
- MILLER, A. H., Publications of the Dominion Observatory, Ottawa, v. 11, nos. 2-6, 1931-1940.
- MILLER, A. H., Gravimetric surveys of 1944 in New Brunswick, *Geol. Surv. Can.*, Bull. no. 6, 1946.
- MILLER, A. H., Gravity investigations of the Dominion Observatory, 1939-1947, *Can. Geophys. Bull.*, v. 1, no. 4, p. 22, 1947.
- MINTROP, L., On the stratification of the Earth's crust according to seismic studies of a large explosion and of earthquakes, *Geophysics*, v. 14, no. 3, pp. 321-335, 1949.
- MISNER, A. D., Temperature gradients in the Canadian Shield, *Trans. Can. Inst. Min. Metal.*, v. 52, pp. 125-133, 1949.
- MOORE, SHERMAN, Crustal movement in the Great Lakes area, *Bull. Geol. Soc. Amer.*, v. 59, pp. 697-710, 1948.
- NORMAN, G. W. H., The Northeast trend of late Pre-Cambrian tectonic features in the Chibougamau district, Quebec, *R. Soc. Canada, Trans.*, 3rd ser., v. 30, sec. 4, pp. 119-128, 1936.
- NORMAN, G. W. H., Thrust faulting of Grenville gneisses northwestward against the Mistassini Lake, Quebec, *J. Geol.*, v. 48, pp. 512-525, 1940.
- PEACH, P. A., A decrepitation geothermometer, *Amer. Min.*, v. 34, pp. 413-421, 1949.
- POMERANTZ, J.; PERKINS, B.; ATANASOFF, J. V.; and BONWIT, K. S., Seismic curves from Helgoland blast of 18 April 1947, *U. S. Naval Ord. Lab. rep.* no. 1080, pt. 1, 1948.

- SCOTT, H. S., The decrepitation method applied to minerals with fluid inclusions, *Econ. Geol.*, v. 43, pp. 637-654, 1948.
- SIEDERHOLM, J. J., The subdivision of the Pre-Cambrian of Fennoscandia, *Congr. Geol. Intern. XI*, C. R., v. 1, pp. 686-693, 1910.
- SLACK, H. A., Radioactivity measurements in the Kirkland Lake area, *Trans. Amer. Geophys. Union*, v. 30, pp. 867-874, 1949.
- SLICHTER, L. B., Cooling of the Earth, *Bull. Geol. Soc. Amer.*, v. 52, pp. 561-600, 1941.
- SMITH, F. GORDON, The pyrite geothermometer, *Econ. Geol.* v. 42, pp. 515-523, 1947.
- SMITH, F. GORDON, The ore deposition temperature and pressure at the McIntyre Mine, Ontario, *Econ. Geol.*, v. 43, pp. 627-636, 1948.
- SMITH, F. GORDON, and PEACH, P. A., Recent advances in the laboratory study of ore, *Can. Min. Metal. Bull.*, v. 42, pp. 351-353, 1949.
- STONELEY, ROBERT, The continental layers of Europe, *Bull. Seis. Soc. Amer.*, v. 38, pp. 263-274, 1948.
- SUESS, E., The face of the Earth, Oxford, 1904.
- THODE, H. G.; MacNAMARA, J.; and COLLINS, C. B., Natural variations in the isotopic content of sulphur and its significance, *Can. J. Res.*, v. B27, pp. 361-373, 1949.
- TUVE, M. A., Annual report of the Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, Year Book no. 47, pp. 60-65, 1948.
- TUVE, M. A.; GORANSON, R. W.; GREIG, J. W.; ROONEY, W. J.; DOAK, J. B.; and ENGLAND, J. L., Studies of deep crustal layers by explosive shots, *Trans. Amer. Geophys. Union*, v. 29, p. 772, 1948.
- TYRRELL, J. B., Report on the Doobawnt, Kazan, and Ferguson rivers and the northwest coast of Hudson Bay, *Geol. Surv. Can. Ann. Rep.*, part F, 1896a.
- TYRRELL, J. B., Is the land around Hudson Bay at present rising?, *Amer. J. Sci.*, v. 2, pp. 200-205, 1896b.
- UMBGROVE, J. F. H., The pulse of the Earth, The Hague, 1947.
- UREY, H. C.; ERSTEIN, S.; MCKINNEY, C.; and MCCREA, J., Method for measurement of paleo-temperatures, *Proc. Geol. Soc. Amer.* (abstract) pp. 65-66, 1948.
- VENING MEINESZ, F. A., Shear patterns of the Earth's crust, *Trans. Amer. Geophys. Union*, v. 28, pp. 1-61, 1947.
- VENING MEINESZ, F. A., Major tectonic phenomena and the hypothesis of convection currents in the Earth, *Geol. Soc. London, Q. J.*, v. 103, pp. 191-207, 1948.
- WEGENER, A., The origin of continents and oceans, New York, 1924.
- WILLIAMS, M. Y., Churchill, Manitoba, Can., *Geog. J.*, v. 39, pp. 131-132, 1949.
- WILLIS, B., and WILLIS, R., Eruptivity and mountain building, *Bull. Geol. Soc. Amer.*, v. 52, p. 1646, 1941.
- WILLMORE, P. L., Seismic experiments on the north German explosions, 1946-1947, *Phil. Trans. Royal Soc. London, Ser. A*, v. 242, pp. 123-151, 1949.
- WILSON, MORLEY E., Pre-Cambrian, 50th Anniv. vol., *Geol. Soc. Amer.*, 1941.
- WILSON, MORLEY E., (editor) Structural geology of Canadian ore deposits, *Can. Inst. Min. Metal.*, 50th Anniv. vol., 1948.
- WILSON, J. TUZO, Some aspects of geophysics in Canada with special reference to structural research in the Canadian shield, part 2, *Trans. Amer. Geophys. Union*, v. 29, pp. 691-726, 1948.
- WILSON, J. TUZO, Some major structures of the Canadian shield, *Can. Min. Metal. Bull.*, v. 42, no. 451, pp. 543-554, 1949a.
- WILSON, J. TUZO, An extension of Lake's hypothesis, concerning mountain and island arcs, *Nature*, v. 164, pp. 147-148, 1949b.
- WILSON, J. TUZO, The origin of continents and Pre-Cambrian history, *Trans. R. Soc. Canada, Sec. 4*, v. 43, in press.
- WOOLLARD, G. P., Gravity anomalies and the nature of the Earth's crust, *Trans. Amer. Geophys. Union*, v. 30, pp. 189-200, 1949.

Geophysics Laboratory,
Department of Physics,
University of Toronto,
Toronto, Canada

(Communicated manuscript received August 3, 1949, and as revised December 16, 1949; related to the Report of the Special Committee on Geophysical and Geological Study of Continents presented by title at the Thirtieth Annual Meeting, April 22, 1949; open for formal discussion until July 1, 1950.)

GEODETIC WORK EXECUTED IN MEXICO FROM APRIL 1948 TO MARCH 1949

Manuel Medina Peralta

(Translated by Maria Perri)

The activities of the Geographic Bureau of Mexico during the period indicated, can be summed up under the following headings: (1) continuation of geodetic triangulations in the country; (2) base measurements; (3) astronomy of position; (4) precise levelling; (5) gravimetry; and (6) cartographic operations.

Geodetic triangulations--Three geodetic expeditions, each consisting of several parties, operated in the field. The first, which was located in the State of Coahuila, was responsible for the measurement of horizontal and vertical angles of the projected triangulation along the 101st meridian, as described in part in the previous annual report [MEDINA, 1949].

At present, this triangulation has been increased by one more quadrilateral; it is assumed that its northern side, Barreta-Barrote, because of its relative proximity to the Rio Bravo del Norte (Rio Grande), will be the side used in connecting with the triangulation of the United States Coast and Geodetic Survey; an operation which is hoped will be realized in the near future.

The triangulation referred to, which is connected to two primary triangulations, namely the Rio Lerma to the south and the 26th Parallel to the north, is of second-order accuracy, the mean error of closure of the 76 triangles comprising the arc being 1.77. According to the tolerance fixed by the Pan American Consultation on cartography, Rio de Janeiro, 1944, the mean angular closure errors for triangulations of this category should not exceed three seconds.

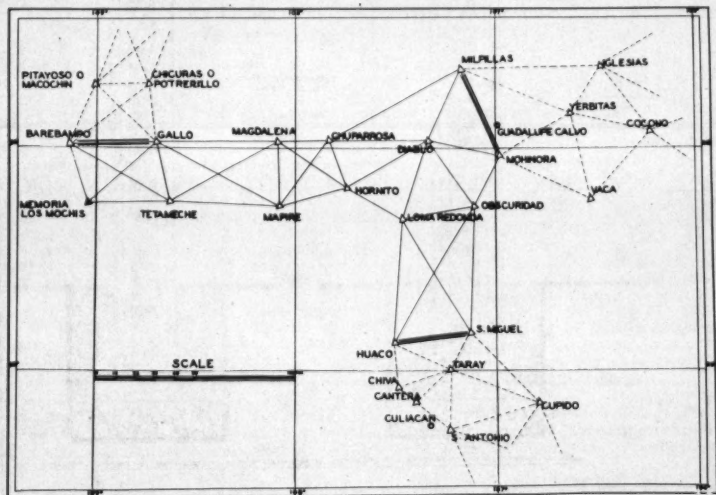


Fig. 1--Linking of the triangulations of Sinaloa-Sonora and the 26th Parallel

securely imbedded in the ground, filled with material found in the locality and made permanent with cement mortar.

Geodetic bases--A site was selected and a new geodetic base was measured in the Isthmus of Tehuantepec, in order to increase the strength of figure by reducing the summation of R_1 and R_2 between the two base extremes of this triangulation, namely those of Oaxaca and Tapachula. The sketch of this base and its expansion is shown in Figure 3.

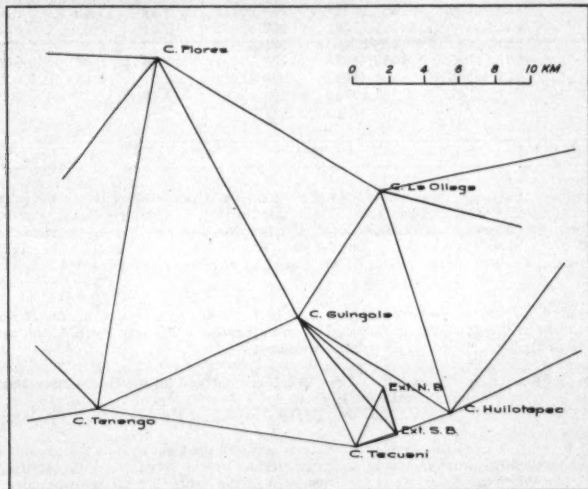


Fig. 3--Base measured on the Salina Cruz-Tehuantepec Highway

This base was measured in the same manner as all bases in Mexico in the last 25 years, with 24-meter invar tapes, supported on tripods, specially designed by this office. Figure 4 gives an idea of the arrangement employed.

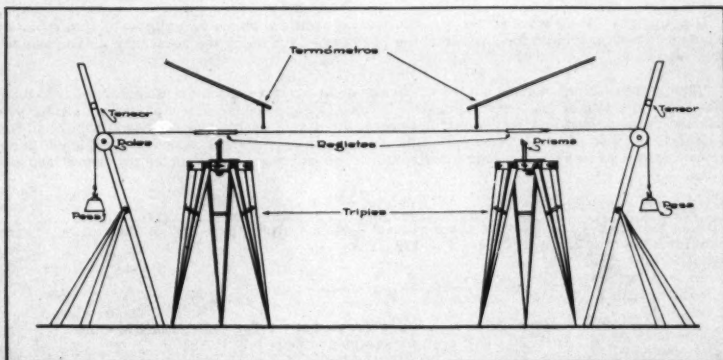


Fig. 4--Apparatus employed in measuring a geodetic base

The results of this base computation are shown in Table 1.

Table 1--Summary of the Tehuantepec base computation

Sections	Forward	Backward	Mean	V	e_p	e_p^2
	m	m	m	mm	mm	
I	959.85905	959.86334	959.86119	2.14	± 1.43	2.0449
II	983.97771	983.97833	983.97802	0.31	0.31	0.0144
III	983.80959	983.80906	983.80932	0.27	0.17	0.0289
IV	1007.74585	1007.74338	1007.74461	1.24	0.82	0.6724
V	983.82959	983.82942	983.82951	0.08	0.06	0.0036
VI	983.85041	983.85132	983.85087	0.46	0.30	0.0900
						2.8542

Probable error ± 1.70 mm Relative error 1/3,470,000

Astronomy of position--Eleven astronomic stations were established during the period covered by this report as follows: Laguna de Jaco, Coah., third-order; E. Socorro, Coah., third-order; Arcocha, Coah., third-order; La Vibora, Coah., third-order; Ocampo, Coah., third-order; La Merced, Coah., third-order; San Marcos, Coah., third-order; Ateneo Fuente, Saltillo, Coah., first-order; El Infante, Coah., Laplace station; Villa Union, Coah., third-order; and Vado de Chizos, Coah., third-order.

As indicated in previous reports, third-order positions are executed by series of equal-altitude observations on the Sun (time and longitude) and altitudes of Polaris (latitude) on two days and their respective nights. The probable errors are about $\pm 3''$.

The Laplace station at the geodetic vertex El Infante, as well as the first-order station Ateneo Fuente, Saltillo, were determined with the Repsold No. 2 Zenital Meridian, by observing meridian passage of stars (time and longitude) and the Horrebow-Talcott classic method for latitude.

Precise leveling--A precise level line was run between the Convento de los Leones (bench mark established in 1945) and the bench mark established by the Direccion de Geografia, Tacubaya, to study the stability of the latter, as it has been used as the datum for the leveling done in the Valley of Mexico, from 1937 to the present. This leveling extended for 21.109 km.

A new leveling was done between the Tacubaya bench-mark and that of Atzacualco (extreme of the leveling run across Mexico City), for the purpose of studying the sinking of the city. This leveling extended for 11 km. Both lines of levels were executed with a Wild N III precise level, employing the special invar metal rods which accompanies this equipment.

Gravimetry--There were no new gravimetric determinations made, while waiting to replace the old pendulum equipment for another of the Brown type, for which the necessary measures are being taken.

Cartography--In the normal course of cartographic advance, which are directed towards the compilation of a new Map of the Republic, scale 1:500,000, we are making use of photogrammetric surveys conducted in the country during the past few years; the sheets Puebla and Tapachula have been completed and published. The Mexico sheet of the world map at 1:1,000,000 was also completed, in accordance with the respective international specification and is at present in the process of reproduction.

Reference

MEDINA, MANUEL, Geodetic work accomplished in Mexico from April 1947 to March 1948, Trans. Amer. Geophys. Union, v. 30, pp. 119-122, 1949.

Oficina de Geografia,
Tacubaya, D. F., Mexico

(Manuscript received April 10, 1949; presented at the Thirtieth Annual Meeting, April 20, 1949; open for discussion until July 1, 1950.)

GEODETIC SURVEYING IN LATIN AMERICA

P. C. Doran

In the United States there is so much activity in surveying, both public and private, that we are liable to ignore or at least to be indifferent to surveys being conducted in other sections of the world. This short discussion on geodetic surveys in Latin America is intended to present an account of extensive geodetic operations now being executed in our fellow Americas.

At Washington in 1943, at Rio de Janeiro in 1944, at Caracas in 1946, and most recently at Buenos Aires in October, 1948, meetings have been held, resolutions have been passed, and standards for geodetic surveys have been adopted. The organization responsible for these meetings is the Pan American Consultation on Cartography under the sponsorship of the Pan American Institute of Geography and History. The member nations of the Pan American Union have banded together to formulate comprehensive plans and to coordinate systematic geodetic surveys of Central and South America, with the ultimate aims of establishing precise geodetic control throughout all of the Americas, of developing a continental datum for South America based on the International Ellipsoid, and of producing accurate maps of these regions. In the province of geodesy, it was resolved that the standards should not be below those recommended by the International Union of Geodesy and Geophysics.

All of the nations included in the Pan American Institute of Geography and History were greatly interested in the proposed work. It was apparent, however, that all the nations did not have equal experience in this work nor adequate equipment for carrying out such extensive operations. The United States has had many years of experience in the matter of geodetic control covering large areas and has already established a common datum for Alaska, Canada, the United States, and Mexico. Drawing on its past experience and on its supply of technical equipment, the United States, through the agency of the Inter American Geodetic Survey, is assisting certain countries in establishing the necessary geodetic control in Central and South America and in the coordination and enlargement of surveys of adjoining countries. The Inter American Geodetic Survey is a civilian organization under the direction of the Army Engineers. At this time, three officers of the U. S. Coast and Geodetic Survey are assigned to work with the IAGS.

Basic geodetic control can be divided into two main divisions - horizontal control and vertical control. The establishment of extensive precise horizontal control requires many diverse operations such as reconnaissance, horizontal-angle measurements, base-line measurements, astronomic observations, gravity studies, and magnetic studies. Vertical control, less complicated than horizontal control, consists of two basic operations - the running of first-order levels and the determination of sea-level datum by means of tidal observations.

Since late 1946, well-planned and closely coordinated efforts have been made to establish geodetic control. The results have been good. They have not been spectacular but have been basically sound and are now being obtained at a gradually accelerating rate. A brief resume of the results obtained is offered.

Reconnaissance, the first and basic operation in obtaining horizontal control, has forged ahead rapidly. Today there exists a continuous net of reconnaissance for first-order triangulation extending from a junction with previously observed triangulation in Mexico (already connected to the United States net on the North American Datum) to a point near the southern end of Chile. From Colombia another arc runs into Venezuela. Reconnaissance has also been completed on certain arcs in Brazil and in Argentina by Argentine agencies. Possible sites for crossing the mighty Amazon have been investigated from the air. Reconnaissance has also been completed in other Pan American countries.

Most of this reconnaissance was done by standard methods. However, two innovations were introduced into this old art. One was the use of regular airplanes for picking out stations in jungle areas and for testing inter-visibility of stations and the other was the use of helicopters for testing lines in the flat areas of Cuba. The jungle area of eastern Panama is so unknown and impenetrable that little headway was made for over a year in the reconnaissance on that area. It was apparent that some new method had to be devised if any progress was to be made. F. S. Tandy, Director of

the Inter American Geodetic Survey, finally hit upon a method which proved very successful in Panama and other jungle areas.

A plane, such as a C-45, or a C-47, or even the small L-5, is used in the aerial reconnaissance. An observer, flying at almost tree-top level over a known hill, was able to obtain its elevation and to see the far horizon and pick out possible hills for the expansion of the figures. Bearings could be taken to likely hills by flying on course for a short time. Distances were found by timed flights, in both directions, between possible hill stations. Inter-visibility could be checked by direct sight. In clear weather, a hundred miles of reconnaissance could be done in a day.

In order to enable the ground party to reach the desired station and to be sure it was at the proper point (quite a task in a rain forest jungle) the reconnaissance plane, after thorough check of inter-visibility, would drop long streamers of aluminum foil from the plane onto the proposed stations. Some of this remained in the tree tops, some hung down toward the ground, and some fell to the ground. This foil, clearly visible in the green of the jungle, was an excellent marker for guiding the ground parties. Where going was particularly bad, the plane guided the ground party to the foil by circling above the station and directing movement of the ground party by radio. The need for foil marking, air guidance, and food by air-drop is apparent from the fact that thirty-two days were needed to reach one jungle station at six-thousand foot elevation.

The helicopter was used in the flat areas of Central Cuba to determine the height of towers needed and to check the inter-visibility of stations. Hovering over a selected station, it offered a stable platform and sufficient time for the observer to obtain angles to proposed stations and to check lines of sight to distant stations.

Directly following the reconnaissance comes the actual horizontal-angle observations. Observations have been made on first-order arcs of triangulation by the countries of Central America in their respective countries. Observations are now in progress across Panama toward Colombia. The one thing I learned during a two-month period in this area was that the only reliable thing was the unreliability of repetition of previous weather conditions. A fifteen-day spell of good weather, usual just between the end of the rains and the start of the real hot dry season, did not materialize. The predicted smoke did not settle in the area as in previous years, and the work was hampered by the water haze which seemed to be constantly in the air due to the steady prevailing north and north-easterly winds. However, survey agencies of each of the Latin American countries have accomplished surveys in sections of their respective countries during the past year.

First-order bases are an integral part of any triangulation scheme. This part of the work is well started. Bases, sufficient in number to control the triangulation in the respective countries, have been measured in certain South and Central American countries and in the Caribbean Islands. Additional bases are contemplated in other South American countries. The reconnaissance for some of these bases, including expansion figures, has been done.

The system of measuring bases with the fifty-meter tape, supported either by stakes or rail, as is the standard method of the U. S. Coast and Geodetic Survey, has been introduced into the Central and South American countries. The rapidity of this method and the fact that it can be used over rather rough ground appeal to engineers, and the system has been wholeheartedly adopted in the countries where it has been demonstrated. All base measurements to date have been well within the specifications for such work.

The necessary Laplace stations for determination of latitude, longitude, and azimuth are being established every six to eight figures along the entire arc of first-order triangulation. As the instruments generally used (Bambergers and Wild T-4's) are very scarce, most of the work to date has been done by IAGS engineers using their own equipment. Instructions were given to the local government engineers so that each country can carry on the work when they receive the necessary instruments and equipment. A few of the countries have had Bambergers for some time, others have just received Wild T-4's, while others have T-4's on order. A number of Laplace stations have been observed in Central America. Others will be observed, as needed, in each country as work progresses.

The standard method of wireless determination of longitude as practiced by the U. S. Coast and Geodetic Survey for some years is being used in the field. The Horrebow-Talcott method of latitude determination is being used. In the Northern Hemisphere, Polaris is used for azimuth determination. In the low latitudes a study is being made to determine, both theoretically and practically, the best method for determining azimuths of required accuracy. In the southern latitudes the IAGS engineers plan to use Sigma Octantes, a circumpolar star very near to the pole. This is a dim star, but it is visible with the powerful instruments now in use in the field.

An extensive gravity survey of the various South American countries has just been initiated. It is planned to establish at least one basic pendulum gravity station in each country and a number of gravimeter stations. This plan, while it does not give a thorough study in each country, does form a basic network of stations from which gravity studies and surveys may be made at a later date with the rapid and accurate gravimeter.

The mention of gravity brings up the question of the method to be used in determining the origin point for a South American datum. The choice of Meade's Ranch in Kansas as the origin for the North American Datum was determined by mathematical study of all existing triangulation and astronomic observations obtained over a great many years. Considering the scarcity of astronomic observations and lack of firm enlacement of first-order triangulation systems in South America could this system be applied to South America in the near future? Could not and should not the method of intense gravity surveys for the absolute determination of the deflection of the vertical, as is now being conducted in sections of the United States, be applied in the near future to some properly chosen area in South America? This would establish an origin and would eliminate the use of isolated provisional datums which eventually would have to be recomputed and adjusted into a final unified system. Possible sites in Argentina and in Brazil are under consideration. Accessibility is a major factor where so many stations must be so definitely placed in relation to point of origin. This matter of origin is being given careful consideration, and it is hoped that a decision will soon be reached.

Although magnetic observations and studies are not technically geodetic operations, they are closely allied and are of the utmost importance in the compilation of maps of any region. A considerable number of magnetic observations have previously been made in South America, but they do not constitute a comprehensive magnetic survey, and much more information is desired. In the late spring of 1949, two magnetic parties left the United States for a very extensive and thorough study of magnetism in South America. These parties are experienced U. S. Coast and Geodetic Survey magnetic observers, collaborating with IAGS and the Latin-American countries. At least two years will be devoted to magnetic observations and studies. Much new and valuable information should be available at the completion of this survey.

In addition to the aforementioned horizontal control operations we must consider vertical control plans.

At present there are 46 primary tide stations in operation in the coastal waters of Mexico and of Central and South America. A few of these stations are operated entirely by the local governments. Some are stations which have been in operation a number of years through the cooperative work of the local government and the U. S. Coast and Geodetic Survey. The stations established within the past two years are the result of collaborative efforts of the IAGS, the U. S. Coast and Geodetic Survey, and the local governments. The data from all the gages are available to all and will be used in the determination of sea-level datum. Each country with a sea coast has at least one primary tide station - other nations with extensive coast lines naturally have a sufficient number of stations to give the desired results.

There has been very little first-order leveling in most of the Latin American countries. The first phase in the establishment of first-order levels is to instruct the local engineers, wherever necessary, in the art of running levels so as to obtain the required standard of accuracy. This program is well under way. The next step is to run first-order levels along the main coastal highways, connecting each primary tide station as the work progresses. This is the main scheme in the various countries at the present time. Considering the great extent of the coast line of the Americas, it is apparent that this basic scheme will require a number of years for completion. Work has been started on this phase and is progressing slowly but steadily. Naturally, some of the smaller countries will soon complete the coastal lines and will go into the third phase of the level work, that is, cross-country and closed-circuit loops of levels. These lines will cover the country and will serve as the basic level net for all mapping and engineering projects.

It has been found that even the most experienced observers cannot take too long a sight under atmospheric conditions existing in these tropical countries. Sixty meters, where terrain permits, is a good length under the best of conditions. Hence the rapid progress as experienced in the United States has not been and cannot be duplicated in these warm countries. As the engineers get more practice in leveling they will naturally gain more speed while still maintaining the required accuracy.

The direction method of observing, with sixteen positions of the circle in relation to the initial station, is being adopted by the southern countries. Observing at night on signal lamps is also being initiated. Vertical angles are measured on heliostopes during the day. A uniform method of recording and computing is slowly being introduced in all the countries. The adoption of these uniform

methods and systems throughout all the Pan American Nations will ultimately produce a homogeneous mass of data, of uniform accuracy, which may readily be adjusted with consistent results over the entire continent.

The Wild T-3 theodolite is the instrument which is being universally used in the execution of the first-order triangulation. This is a very compact, precise instrument which is giving excellent results. Many of the nations now possess these instruments. Those who do not have any on hand now have ordered some from the makers.

The U. S. Coast and Geodetic Survey precise level is being introduced into many of the countries for the level work. The standard invar rods are used with this instrument. A few of the countries have their own precise levels, mainly the Wild N III. This instrument, with its proper invar rod, is giving good first-order results.

The Bamberg broken-telescope transit is being used on some of the astronomic work. A newer instrument, the Wild Universal Theodolite T-4, has been tested and used in the field for precise astronomic work. This T-4, a very neat and compact instrument, has given excellent results. The IAGS and many of the countries have T-4's on order and are eagerly awaiting delivery.

All tide gages installed on a collaborative basis are the U. S. Coast and Geodetic Survey standard automatic tide gages. Usual tidal bench marks are set at all tide stations. In order to speed up the installation of the gages, a portable tide gage house has been developed and is proving very successful.

In gravity work the basic stations are established with the Brown pendulum apparatus. A Worden gravimeter, recently secured by the U. S. Coast and Geodetic Survey, is being compared and calibrated with the pendulum apparatus and is being used to establish additional stations. The results being obtained with this gravimeter are excellent. The gravimeter, with its lightness, compactness, speed of operation, and great accuracy, seems destined to be the gravity instrument of the future.

Many basic items and methods, tested and proved in the past, are being used on this project. Bilby steel towers are used where needed in flat or wooded country. Substantial concrete monuments, with subsurface marks, are being used to mark all triangulation stations. Standard brass discs and heavy concrete monuments are being established as bench marks. Maximum spacing of these bench marks is about three kilometers. Good descriptions of all bench marks and triangulation stations are being written. This has been rather neglected in the past, but its importance is now being stressed. Standard U. S. Army vehicles - jeeps, weapons carriers, ambulances, 2 1/2-ton six by sixes, 1/4-ton trailers and one-ton trailers - are being used throughout the project. A new jeep station wagon, with four-wheel drive and windlass forward, is also being used. The famous LCM's are being used to advantage in certain sections for moves from station to station in coastal waters.

Let us go, for a moment, from the practical to the speculative. A start has been made on this far-reaching project. Years will be required to accomplish all the aims aspired to by the Pan American Nations. What new facts will be made available to geodesists? Consider the possibilities of obtaining valuable scientific information from an unbroken arc of first-order triangulation extending from Nome to Cape Horn. Will the deflection of the vertical along the Andes arc tend to swing the triangulation unduly in azimuth? Will a new figure for the size or shape of the Earth be forthcoming? Will gravity studies reveal abnormal anomalies? Will shorean be sufficiently developed to be used to span some of the tremendous jungle areas of the lower Amazon basin?

We do not know the answers to these or to many other questions. But there certainly is sufficient promise of exciting and revealing information to spur all the nations of the Americas to do their utmost towards the completion of this tremendous undertaking.

United States Coast and Geodetic Survey,
Washington 25, D. C.

(Manuscript received April 21, 1949; presented at the Thirtieth Annual Meeting, Washington, D. C., April 20, 1949; open for formal discussion until July 1, 1950.)

DISCUSSION OF
"SUPERCOOLING AND CRYSTALLIZATION"
by J. Ross Heverly

[Trans., v. 30, pp. 205-210, 1949]

John C. Johnson (Massachusetts Institute of Technology, Cambridge, Mass.)--The writer would like to present some data obtained during the spring of 1948 on observations of the spontaneous freezing temperatures of supercooled water drops.

The apparatus used consisted of a thermally controlled chamber at atmospheric pressure. The drops of distilled water were suspended from paraffin-coated Wollaston wire or glass fiber after the technique of HOUGHTON [1933]. The temperature of the drops was measured using a thermocouple located one centimeter below the drop. Theory [HOUGHTON, 1933] and test showed that when the ambient relative humidity (the relative humidity of the surrounding air at a great enough distance from the drop so as to be unaffected by the evaporation from the drop) is at saturation, the ambient and drop temperature are the same. In experiments with supercooled water drops under isothermal ambient conditions, some evaporation of the drop occurs. This is explained by the fact that the drop has a vapor pressure saturated in respect to its own water surface while the chamber is saturated in respect to ice particles on its walls. This results in the chamber being slightly unsaturated in respect to the vapor pressure of the drop. The question immediately arises as to the validity of the temperature measurements of the drop using the ambient temperature when the ambient temperature is changing. Experimental evidence indicates that the surface temperature of a drop in the range of radii used (150 to 1700 microns) follows the changes in the ambient temperature and relative humidity so closely that the total error in measuring the surface temperature of the drop by means of the ambient temperature is believed to be not in excess on one degree C. The direction of the error is such that the drop is colder than indicated by the ambient temperature.

Rates of cooling and warming of the drops varied from as little as $0.1^{\circ}\text{C}/\text{min}$ to $7^{\circ}\text{C}/\text{min}$, while the duration of supercooling varied from one to 95 min with a mean of 12 min. Fifty sets of measurements were made.

Figure 1 is a scatter diagram of the spontaneous freezing temperature of these water drops plotted against their radii. It will be noted that although the highest freezing temperature (-15°C) is attained by a drop of 1470 microns diameter, and the lowest freezing temperature (-38°C) is attained by a drop of 680 microns diameter, the diagram also indicates that drops of 150, 780, and 1750 microns all froze at -25°C . It appears from these data that the mass effect on the spontaneous freezing point of water drops is not a well defined function. If a single curve were to characterize these data, it would probably approximate a straight line in this region, as shown by the solid line of Figure 1. Extrapolation of this curve to greater diameters is meaningless, first because of the scatter, and secondly because this curve would intersect the 0°C or melting isotherm at less than four mm diameter while the largest water drops may extend to a diameter of seven mm. Thus if any curvature were to be indicated it would be such as to approach some isotherm equal to or less than 0°C asymptotically.

Heverly's freezing curve from his Figure 2, page 207, is included as the dashed line of Figure 1. It is interesting to note that both sets of data tend toward a value between -35°C and -40°C for the spontaneous freezing point as the drop diameter approaches zero. This is in good agreement with experiments conducted in cold boxes and expansion chambers where the drop diameters are of the order of one to ten microns.

An alternate view of the data of Figure 1 is to consider that the data scatter such that there is no significant variation of the freezing temperature with either mass or duration of supercooling. This was done by JOHNSON [1948] to give the histogram of Figure 2. From this is obtained a probability function with a maximum at -28°C . Such a method of analysis was used because the mass of the drop was constantly changing as was the temperature of the chamber. The changes were slow but at a measurable rate. Therefore, should mass, time, and nuclei from the surrounding air be

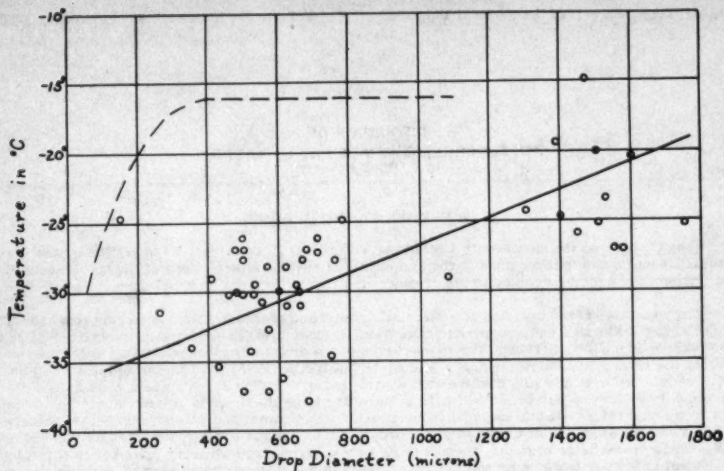


Fig. 1--Relation of spontaneous freezing point of water drops to drop diameter

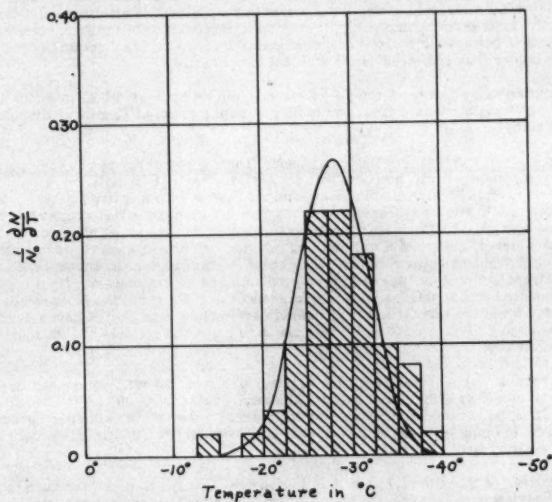


Fig. 2--Histogram of the fraction of the total number of drops frozen in a 2.5°C temperature interval ($1/N_0 \frac{dN}{dT}$) plotted as a function of the freezing temperature

considered as significant but unknown factors contributing to the spontaneous freezing of a water drop, the necessary control to evaluate these factors is lacking in the data presented in Figures 1 and 2. However, in order to obtain this control there would be required, among other things, scrupulously sterile laboratory conditions with the collection of an exhaustive amount of data. This would make the application of these drop studies to the atmosphere quite artificial. Very careful work along these lines has been done by DORSEY [1948] who used sealed vials of water rather than drops, so that his results are not strictly comparable to this work. Thus, there is some justification for treating the data presented as a distribution function. It appears that no special meteorological significance can be attached to the value -28°C or to the details of the distribution curve because in the atmosphere freezing is undoubtedly facilitated by collision between supercooled drops.

In conclusion, the effect of duration of supercooling, thermal path, and the time rate of change of ambient temperatures on the freezing point of a drop of water was investigated. The results for a typical drop are given in Figure 3. It is concluded that none of these effects is important in determining the spontaneous freezing temperature of a drop of water. It furthermore suggests that the spontaneous freezing point is not a unique temperature for a water drop in air.

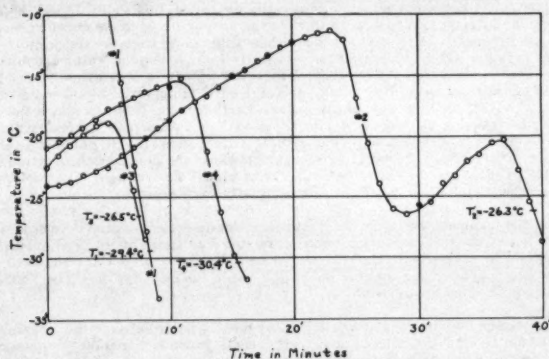


Fig. 3--The thermal path of one drop of water that was successively frozen and melted; the numerical values are the temperatures at which the drop froze on each run; evaporation changed the drop size from an initial diameter of 1611 microns to a diameter of 1083 at the end of Run 4

References

- CWILONG, B. M., *Nature*, v. 155, pp. 361-362, 1945.
 DORSEY, N. E., The freezing of supercooled water, *Trans. Amer. Phil. Soc.*, v. 38, pt. 3, 1948.
 HOUGHTON, H. G. *Physics*, v. 4, p. 419, 1933.
 JOHNSON, J. C., A study of the freezing temperatures of supercooled water with special reference to drops having diameters from 150 to 1700 microns, Thesis, Sc. D., Mass. Inst. Tech., July, 1948.
 SCHAEFER, V. J., The production of ice crystals in a cloud of supercooled water droplets, *Science*, v. 104, pp. 457-459, 1946.

J. Ross Heverly (United States Naval Academy, Annapolis, Maryland, Author's closure)--In agreement with the data which I obtained in the summer of 1947 [HEVERLY, 1948] Johnson has found that duration of supercooling, thermal path, and time rate of change of ambient temperature did not affect the spontaneous freezing point of a drop of water. In disagreement with my data, Johnson obtained a mean of -29°C for the spontaneous freezing point of a drop in the diameter range of 400 to 1600 microns, whereas I obtained a value of -16°C for a drop in the diameter range of 400 to 1100 microns. Although Johnson's Figure 1 indicates a definite effect of drop size on spontaneous freezing point, this effect appears to be of a different nature than the one found by me. The temperature measuring technique employed by me can hardly be held responsible for this discrepancy because, as Johnson correctly points out, any evaporation from the droplets would have to result in a lower

temperature, while the temperatures found by me were higher. Also, according to Johnson, a difference in temperature measuring technique could account for a temperature difference of one degree C. It may be noted that, for the droplets on wax paper, the thermocouple was two mm away from the drops; nevertheless, the results for these droplets fall well in line with those obtained when the droplets were supported by the thermocouple. Moreover, the scattering of individual data obtained by me is less than half of that shown in Johnson's results. Unfortunately, in the drop size range below 200 microns, in which I found the most pronounced size effect, Johnson's data show only a single measurement, so that a comparison of our results in this range is not possible.

The "sterile laboratory conditions" and "the collection of an exhaustive amount of data" referred to by Johnson are the counterpart of many laboratory investigations and are necessary to determine the nature of substances which may affect the spontaneous freezing point of water drops. The research of Vonnegut in isolating silver iodide as such a substance is an excellent illustration. Until their presence was realized, minute traces of silver in the laboratory atmosphere and contamination of the silver iodide caused perplexing and misleading results.

d'ALBE [1949] has recently examined artificially produced substances as well as those present in outdoor air in an attempt to throw some light on the properties of these substances which may influence their effectiveness. With ordinary air, d'Albe finds that, when the temperature reached during expansion falls to below -32°C , ice crystals are usually seen among the water droplets. The ice crystals are not numerous unless the temperature falls below -41°C , in which case a fifty-fold increase takes place. These data agree well with the -28°C to -38°C temperatures and an estimated forty-fold increase given in Table 1, p. 209, of my paper. Furthermore, d'Albe's conclusion that ice crystals are formed by freezing that occurs during the growth of a droplet is in conformance with a freezing point-versus-diameter relationship. The higher critical temperature obtained in my investigation, -28°C as contrasted with d'Albe's -32°C , may be due to the fact that observation of replicas of the condensation products was made rather than direct visual observation. The replica method would seem to be superior in the detection of the initially rare crystals.

The size of the chamber would also be a factor in the detection of rare crystals. Using a relatively large scale chamber so as to observe an estimated five liters of fog, PALMER [1949] recently reported a range of 50 crystals/liter at -31°C to 0.1 crystal/liter at -17°C . The rare crystals may be important in cloud processes. Palmer estimates one to ten per liter would be sufficient for each rain drop to originate as an ice crystal.

There seems to be no immediate explanation for the disparity between the freezing point data obtained by Johnson and that obtained in my investigation. In view of this fact it appears desirable that the experiments be repeated, preferably with an extension of the droplet range to greater and smaller sizes than were investigated thus far.

Corrigendum--The following correction is noted in this paper as published: Figure 2, p. 207, should have a plus within the first circle $\oplus$ after "(a) SUBLIMATION."

References

- d'ALBE, E. M. F., Some experiments on the condensation of water vapour at temperatures below 0°C , Q. J. R. Met. Soc., v. 75, pp. 1-16, 1949.
 HEVERLY, J. R., A study in atmospheric condensation. Thesis, Ph. D., Penn. State College, Jan. 1948.
 PALMER, H. P., Natural ice-particle nuclei, Q. J. R. Met. Soc., v. 75, pp. 17-22, 1949.

DISCUSSION OF "A REFERENCE PLANE OF FLOOD VOLUMES IN THE SACRAMENTO-SAN JOAQUIN BASIN, CALIFORNIA"

by John W. Kuhnel

[Trans., v. 30, pp. 98-115, 1949]

Henry W. Anderson (California Forest and Range Experiment Station, Berkeley, Calif.)--Kuhnel has developed a reference plane of rare floods by use of graphical correlation of 148 watersheds as represented by four parameters of each watershed - area, mean elevation, orientation, and mean annual runoff. He has pointed out the advantages of a correlation approach to flood estimation. Correlation analysis is probably the most promising tool for obtaining approximate answers to many problems in applied hydrology. The nature of these problems makes this statistical approach particularly appropriate, for the problems typically involve a multiplicity of interacting variables. The

use of correlation analysis in new to hydrologic studies. It might be said that these studies are now in only the early stages of the "trial and error" process which according to WILSON [1948] characterizes the statistical approach. In these early stages, criteria are needed upon which to evaluate the contributions and limitations of each new study.

In a recent paper, [ANDERSON, 1949], I suggested six criteria upon which the adequacy of a study in applied hydrology might be evaluated. These were: (1) were the data used representative in space; (2) were the data representative in time; (3) were the effects measured representative of actual effects; (4) were the effects measured related to the desired end product; (5) was a suitable measuring device employed; and (6) were tests made for individual cases and adjustments made in the estimated values to make them meet the actual values? Other criteria might be applied, but I should like to elaborate further on these criteria and examine Kuhnelt's study in their light, employing the same numbers as above.

(1) Spatial representation in a study employing multiple correlation analysis is met when (a) the data used include areas with all magnitudes and combinations of the variations between evaluated variables, and (b) exclude from the universe of study areas with gross variations in unevaluated variables. In this connection the data of Kuhnelt's Table 1 might well have been restricted to the Sacramento - San Joaquin group as was the later application. Otherwise, Kuhnelt's data are well represented in space; as always, more parameters would have improved spatial representation.

(2) Representation in time is met in correlation analysis when (a) the data included are a "fair" sample of all combinations of the variations in meteorological and other time-associated variables, or (b) time itself is included as an independent variable. A "fair" sample requires more than a long record, it requires that the data selected be balanced with regard to variations in those evaluated variables which may be correlated with time. Although Kuhnelt's study employed the whole period of discharges in an attempt to get time representation, the period of record for each watershed was variable, ranging from three to 54 years. A method of putting discharge records on a common time basis by correlation between discharges between watersheds has been given by LONGACRE [1948] and by correlation with flood "causes" by ANDERSON [1949]. An attempt to estimate the practical consequence of failure to do this in Kuhnelt's study will be made under criteria (3) and (4).

(3) Under the criteria of whether the measured effects were related to actual effects come the choice and definitions of variables and expressions of the functions between variables. Basically, Kuhnelt's dependent variable is the recorded discharges. These are the actual effects themselves and Kuhnelt has been careful to test them for possible errors and make corrections. As he points out the actual discharges are much better indices upon which to build a study of floods than are hypothetical floods built up by storm transposition methods. Kuhnelt has called the dependent variable of discharge the "reference plane" and describes it as follows: "This reference plane of flood-runoff volumes was intended to represent a flood that would be exceeded in magnitude only on relatively rare occasions." In view of the variable period of record, the reference plane might more specifically have been defined as the "maximum flood during the period of record."

Other things being equal, the maximum discharges would be expected to be higher for the longer periods of records. A test for this was made for maximum one-day discharges for watersheds whose area was between 10 and 100 sq mi (data from Kuhnelt's Table 1). The test was statistically significant and showed that the maximum discharge increased by 0.6 inch or about 20 per cent for each increase of ten years in the period of record. Thus, the data upon which the reference plane was based were not at the same level for all watersheds. However, this might mean only that an average, somewhat lower, level than the rare flood has been obtained, with the functions in the correlation diagrams still being valid. For this to be true no significant correlation between any of the evaluated variables and the length of record should exist. Unfortunately, only in recent times have many small streams been gaged. And as shown in Figure 1, the proportion of watersheds of small area is strongly correlated with the length of record. In this figure we see that whereas 90 per cent of the gaged watersheds with periods of records less than eight years are small (less than 400 sq mi in area), only 30 per cent of the watersheds with about 50 years of records are small. Thus, Kuhnelt's discharge-area diagrams have confounded in them the effects due to relationship of discharge and area to the length of record. If the curves were fitted to the data as a whole, this would be expected to result in too small estimates of the maximum discharges for small watersheds.

Next, Kuhnelt's independent variables might deserve inspection. The use of the mean annual runoff as an index of wetness seems of questionable value. When mean annual runoff is known the stream has a discharge record. That record in itself, by proper extension to a long-time record, is probably the best index of future floods for that stream. In estimating discharges for a stream with no records it would be necessary, according to Kuhnelt, first to estimate mean annual runoff by using

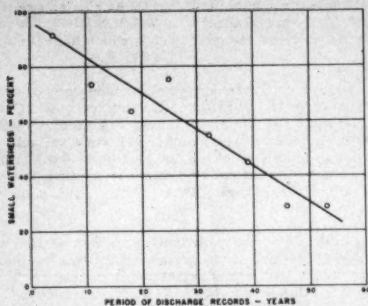


Fig. 1--Variation of the proportion of watersheds less than 400 sq mi in area, with the length of the period of discharge records

extension of data as used by LONGACRE [1948] or ANDERSON [1949] would have overcome some of the difficulty; however, it must be admitted that until discharge records are much longer than they are now, estimates of the infrequent events must be considered as approximations. Nevertheless, putting the reference plane on a comparable time basis by defining it in terms of frequency seems desirable. The degree of protection can probably best be evaluated on the basis of the frequency of floods under each level of protection. Frequency is inherent in the methods employed in flood-control evaluation by both the United States Corps of Engineers and the United States Department of Agriculture.

(5) As to the criteria of suitability of the measuring device employed, Kuhnelt has chosen graphical analysis. This method has become popular lately as evinced by several studies reported in the *Transactions* of the American Geophysical Union. It might be well to compare the graphic method with the method of least squares correlation and regression analysis. Graphical correlation has the following advantages: (a) The method is simple. (b) The form of the functions between the variables need not be decided in advance, but may be adjusted as the analysis proceeds at the discretion of the analyst. (c) The method is relatively rapid when only a few variables are to be studied.

Among the disadvantages of graphic correlation are: (a) No measure of the reliability or significance in a probabilistic sense is obtained either of the effects of individual independent variables on the dependent variable or of the estimation of the dependent variable from all of the independent variables acting together. For any reliable estimate of the correlation existing in the universe it is necessary that the functions be set up on deductive grounds and then tested. The method of graphic correlation consists essentially of fitting a wide variety of functions and choosing the one that gives the highest correlation. Thus, this method has no inherent basis for hypothesis testing or for setting up a rule for decision based on probabilities. (b) The method is subjective and the results are not reproducible since there is merely ocular fitting of the data. (c) As usually applied, the only joint effects evaluated seem to be between the variables placed adjacent to each other in the analysis diagram. (d) No equation is obtained.

Least squares correlation and regression analysis avoid the above disadvantages of graphical correlation analysis. Other advantages of the least squares technique are: (a) Consideration is more likely to be given to other statistical safeguards such as defining the universe of study and attempting to obtain a representative sample. (b) Use of many variables is possible and new machine analyzers may be employed and data running into the thousands analysed with little difficulty.

Disadvantages of the standard least squares technique are: (a) Only the more general techniques are given in texts on the subject such as that by EZEKIEL [1941]. Many problems in hydrology seem to require more elaborate techniques. (b) With more than about ten variables interpretation of the results may be difficult. (c) Certain joint relations of variables cannot be represented simply. However, none of these disadvantages are met by graphical methods.

precipitation data and then from this to estimate the maximum runoff. For streams without discharge records a direct relation of discharges to precipitation would probably be better. Mean elevation is apparently a highly useful simplification of elevational effects. Orientation might be improved by combining it with latitude especially for the snow-melt floods. As Kuhnelt says these parameters can probably be improved upon and other parameters might well be added, but that may well be true of all studies for a long time to come.

(4) Are the effects measured related to the desired end products? The desired end products are (a) information upon which to base design of flood-control structures, and (b) indices of the degree of protection furnished by flood-control projects. The basic root of the problem has been considered by many to be the frequency of discharges from watersheds. Kuhnelt says that attempts were made to put his reference plane on a frequency basis, but difficulty as to what was the true frequency of the infrequent floods made this seem impossible. Perhaps the methods of

(6) Under the final criteria of comparison of the individual estimated values with actual values we see that Kuhnelt made a check; but its use needs clarifying. He says (p. 106): "The depth of runoff from streams located in the Sacramento-San Joaquin Basin was determined by use of graphical correlation diagrams and compared with the maximum recorded depth. For winter rain runoff, the maximum recorded depth from 16 streams or an average of about six for each period of duration studied (1, 3, 5, 20, and 40 days), is very nearly the same as the correlated value of runoff. These streams, where the correlated and recorded values of runoff are very nearly the same, form the control or establish the ceiling for each correlation diagram . . . These controls are scattered throughout each correlation diagram and each determines the location of one particular section of a parameter. The basis for establishment of intermediate values is one of logical symmetry."

It does not seem best to use only six watersheds to establish the location of the lines in the diagrams merely because the data for these watersheds gave agreement between the estimated and recorded values. Such agreement might well have occurred because of chance compensation of errors between two or more variables. It would seem that such a method throws away more than a hundred data and uses only six. The mass of the data for the Sacramento - San Joaquin group, some 115 in all, would provide a better basis for adjustment of the correlation diagrams. What are the consequences of adjusting to six data?

I took a random sample of 20 watersheds from the 115 in the Sacramento-San Joaquin group (watersheds 17, 20, 21, 25, 30, 33, 34, 35, 37, 39, 45, 51, 57, 75, 75, 77, 79, 80, 85, 105). Computing the maximum one-day runoff from the values of the parameters of these watersheds by using Kuhnelt's Figure 3 and comparing the computed with the recorded values gave a rather surprising result. In every case the computed was higher than the recorded values, ranging from only 1.05 to 3.8 times the recorded value, and averaging 74 per cent higher for the 20 watersheds. The average recorded maximum one-day runoff was 1.81 inches whereas the computed was 3.15 inches. Are the diagrams given by Kuhnelt intended to give enveloping curves rather than fits of the data or have the curves, perhaps, been adjusted to give reasonable design discharges?

It is impossible to say how different the results as reported by Kuhnelt would be from the results of another study in which the basic runoff data were first converted to a comparable period of record, and then correlated by homogeneous areas, using multiple regression analysis by the method of least squares. In my opinion, the latter would give somewhat more reliable results. It would seem that the importance of the problem justifies the use of the best methods even at the expense of more time. However, it must be recognized that practical expediency almost always limits the time available to get answers, and approximate methods may sometimes have to be used. That approximate methods seem to be becoming "standard" seems regrettable. It might be better to meet these demands for speed by taking advantage of time savings obtainable by improving calculation methods, that is, punch-card processing of data and machine analysis, rather than by resorting to oversimplification of methods and consequently obtaining rather uncertain answers.

It should be emphasized that Kuhnelt's treatment has been helpful. His discussions are excellent on the merits of correlation of runoff as an approach to flood estimation, and on the limitations and difficulties of the method involving storm transposition and infiltration determinations for mountainous areas. His observations on the influences of topographic and exposure factors on floods will greatly help in setting up other studies of floods and their causes. His suggestion that corrections in reported discharge data be assembled and prepared for insertion in the proper places in the Water Supply Paper of the United States Geological Survey should be carried out.

References

- ANDERSON, HENRY W., Flood frequency and sedimentation from forest watersheds, Trans. Amer. Geophys. Union, v. 30, pp. 567-583, 1949.
 EZEKIEL, MORDECAI, Methods of correlation analysis, John Wiley, New York, 531 pp., 1941.
 LONGACRE, LEONARD L., A representative period for a water-supply study, Trans. Amer. Geophys. Union, v. 29, pp. 682-687, 1948.
 WILSON, WALTER T., Some semantic aspects of hydrometeorological research, Trans. Amer. Geophys. Union, v. 29, pp. 897-902, 1948.

John W. Kuhnelt (U. S. Engineer Office, Sacramento, California, Author's Closure)--Anderson has pointed out some pertinent facts concerning the data presented and the method of analysis which are of considerable interest and which should be of help to anyone making a similar study. Much has been written and many formulas have been developed concerning peak flow but very little apparently has been done in regard to flood volume, especially for long durations of time. Shape of

stream basin and pattern of drainage system although very important in the consideration of instantaneous maximum or peak rate of runoff, are of secondary importance when analyzing total volume of runoff. By eliminating the shape and pattern factors the remaining factors that influence runoff can be more readily analyzed.

Employing the same numbers used by Anderson the following comments are offered:

(1) Table 1 includes data for many streams outside of the Sacramento-San Joaquin Basin. It is believed that with sufficient time, correlation diagrams or formulas can be developed applicable to the entire State of California. Parameters in addition to those used in the study are needed, and perhaps the one of mean annual runoff may be eliminated. Time limitations did not permit exhausting the possibilities of developing such correlation diagrams. Considerable time and expense were involved in assembling the data shown in Table 1 so they were published for the availability of other engineers desiring to make similar studies. The listed data also furnished a convenient record of the maximum recorded runoff of all of the principal streams in California.

(2) Runoff data from any stream on which major runoff had been recorded were used regardless of the length of record available. The study was based on the maximum recorded runoff of each stream so only one value for a given duration of time was used. For instance, if on a stream with 50 years of record available the maximum one day volume of runoff occurred on December 10, 1937, no use was made of the remainder of the record; the only purpose being to establish that a greater volume of runoff had not occurred on some other day. It was believed desirable to use in the study only actually recorded data even though, as Anderson has pointed out, a deficiency exists on runoff records from small watersheds.

(3) There is considerable doubt as to mean annual precipitation being superior to mean annual runoff as an index of maximum volume of runoff for various durations of time. Both factors were considered while making the study and mean annual runoff was found to give the best correlations. Not enough data are available to state definitely why this should be true but part of the reason may be due to the difference in the accuracy with which each can be computed. The headwaters of many of the streams used in the study are located in the high mountainous areas of California. Very little precipitation data are available for these areas and any value of mean annual precipitation for them is largely based on estimated isohyets.

The correlation diagrams presented in the study are probably the best that could be developed with the time limitations that existed. Given sufficient time better ones could no doubt be developed. The addition of latitude of the stream basin and height of barrier ridges appear to be of great promise. With the addition of such new parameters it might be possible to eliminate the need of using mean annual runoff as a parameter and also to develop a diagram applicable to the entire State of California.

(4) The writer is in complete agreement with Anderson in regard to the desirability of the frequency approach as a method of putting the reference plane of flood runoff on a comparable time basis. It is believed that the frequency method will eventually be widely employed to establish the degree of flood protection provided and even the proper magnitude of spillway design floods but that at least 50 and perhaps 100 more years of runoff record will be required before sufficient data are available to define accurately the magnitude of rare floods.

(5) Graphical analysis was chosen because, as Anderson points out, it is simple and relatively rapid. The study presented was made for a specific purpose and with only limited time available. This limitation did not permit the development of formulas or the use of mathematical analysis as suggested by Anderson. It is believed that such analysis would be highly desirable and that it is quite possible that the correlation diagrams could be superseded by a rational formula.

(6) The diagrams presented in the study were developed so as to be representative of the maximum volume of recorded runoff. They are essentially envelope curves, cross plotted for the various durations of time. As envelope curves they can pass through only a limited number of points. Other methods of analysis as suggested by Anderson might yield additional information concerning the effect of various factors on the volume of runoff which were not brought out by the envelope curve technique which was used.

Anderson expresses his approval as to the need of a better method than is now in use of publishing corrections to water supply papers. A number of other engineers have expressed similar views to the writer. There is certainly no doubt that there is considerable need of making the older books more reliable and readily usable. Another suggestion would be for the United States Geological Survey to republish the older books perhaps consolidating five or ten years of record in one volume.

DISCUSSION OF
"COMPARATIVE RAIN MEASUREMENTS AND RAIN-GAGE PERFORMANCES
ON A STEEP SLOPE ADJACENT TO A PINE STAND"

by G. L. Hayes and J. Kittredge

[Trans., v. 30, pp. 295-301, 1949]

Walter T. Wilson (Redwood City, California)--Hayes and Kittredge have contributed useful quantitative information to the old and possibly never-ending problem of measuring precipitation. That the problem is old is indicated in a paper written by Abbe in July 1899, which appeared 50 in the Monthly Weather Review, where he cited articles which were about 50 years old at that time. The authors are to be commended for demonstrating a profile of rainfall catch from the edge of a clearing to a distance where the catch seems to be uninfluenced by the trees. Further, it is gratifying to see two such profiles, thus showing not only an average distribution of catch, but also indicating its variability. The validity of the profiles is based on consistent instrumentation, which, in this case, was a set of gages tilted uniformly. It is regretted that details of wind force and direction were not reported. In view of the statement that much of the rain came with southeast winds, and with the map showing the pine stand to the southwest of the gages, the important question still remains: How far do the effects of a timber stand extend to gages down wind from its edge?

There is a tendency for proponents of tilted gages to extrapolate their enthusiasms beyond their own plot experiments, and to suggest general superiority of tilted gages over standard gages. Suggestible readers, who do not consider the practical aspects of the problem, occasionally inquire of the Weather Bureau why we continue to measure rainfall in our old-fashioned way. Therefore it seems appropriate now to examine some of the limitations of tilted gages, and to indicate some of the reasons for the general acceptance of vertical gages having horizontal circular orifices.

First it may be helpful to discuss the concept of true or representative catch. The authors apparently believe implicitly in such an abstraction which they regard as an inherently correct, though possibly esoteric, element, and which they term "true rainfall." If they were to rely on objective observational data, and an operational definition, the term might go begging. They have implied that, in a group of different types of gages, the one measuring the most rainfall is the one that most nearly indicates true rainfall, and is therefore the best. To produce this large rainfall they have aimed the gage opening in the direction from which the wind blows a major portion of the rain, and then have added about seven per cent because the gage orifice is not horizontal. The question logically arises whether the resulting "measurement" is not larger than it should be.

As the authors state, the obstruction of an upright cylinder into a rain-bearing air stream affects the circulation of the stream and the distribution of the rain-drops as they precipitate. Any interruption of the ground surface, be it a projecting object or, conversely, a trough, produces eddies and standing waves. The assertion that a trough is aerodynamically efficient is questionable, even when one considers no more than its lack of symmetry with respect to wind blowing from various directions with respect to the axis of the trough. Possibly the famous Koschmieder gage comes nearest satisfying those who conceive of a true catch, but even this remarkable installation has its admitted practical deficiencies. It seems more important for gages to give consistent and comparable results than to meet the subjective requirements of an imaginary true catch.

To gain perspective in this problem, it is necessary to consider the magnitude of the trigonometric functions involved. The 40 per cent slope in the authors' experiment has a secant of about 1.07. A 25 per cent slope has a secant of only 1.03. This means that in topography flatter than 25 per cent, differences of less than three per cent are involved, which may be regarded as particularly unimportant in view of the other problems such as estimating areal distribution of rain by means of a limited number of gages. It is also necessary to consider the geographic and areal scale involved. In the United States there are about 10,000 precipitation gages for a total area of about 3,000,000 sq mi, providing an average density of one gage per 300 sq mi. In a large area of heterogeneous topography there is the practical difficulty of deciding where and how far to measure the elements that define the slope of the area each tilted gage is to represent. The western slope of the Sierra Nevada rises 8000 ft in about 80 mi, the average slope thus being about two per cent. Within this slope are areas having diameters as large as a mile with average slopes of 25 per cent. Within these mile-diameter areas are smaller areas having still steeper slopes. How is one to decide what diameter to use for the area his tilted gage is to represent? For each facet of ground surface to be represented by its own gage, the number of gages and observers would be fantastic. Furthermore, topographic parameters are not sampled by naively asserting that each gage represents a facet. The work reported by Hayes and Kittredge does not demonstrate that position on a slope is an

unimportant factor. Had the trough gages been much more than 55 ft apart, on this 600 or 700 ft slope, very likely their catches would have been significantly different. There is no a priori indication of where, on a facet, a single gage would measure the average depth of rain falling on the facet. To burden further the problem of sampling a large rugged area with tilted gages, the ordinary map, being a projection on a horizontal surface, is too simple. With tilted gages there would be the laborious and complex task of literally covering the mountains with trigonometric functions.

Except in the Southeast, and along a narrow zone extending west and up the Pacific coast of the United States, snowfall is an important component of precipitation. It is difficult enough to measure snow without having it pile up on the non-vertical surfaces of tilted gages, where it would modify the aerodynamics of the receivers and obstruct the orifices. These and other practical considerations are sometimes neglected in advocating not only tilted gages but vecto-pluviometers and other complicated devices.

The reason for setting the tilted gage with its orifice parallel to, and its axis normal to, the generalized local surface seems to stem from a belief that air moves parallel to the ground surface, thus leaving the gage catch to be determined by the free-fall component of the motion of the rain drops. Anyone who has carefully observed the motions of raindrops and snow flakes during a variety of storms, knows that with strong winds there are large and small eddies, with motion in all directions and angles. Thus a tilted gage, as any other gage or trough, has the wind blowing into it at times, and even in the opposite direction at times. There is little doubt that a shield, such as that developed by Alter, does reduce the effects of eddies in the vicinity of a gage. The shield is flexible, so that its movement enables it to shed snow. The circular horizontal orifice with vertical cylinder has the same position at every station, unaffected by judgment as to what direction and angle to choose.

The orifice of the standard gage is normal to the direction of gravity, which is the non-wind component of the motions of the precipitating rain drops. The orifice is parallel to the projected surfaces conveniently portrayed by ordinary maps. With a plumb installation there is little problem of unequal settlement, weakening of the gage support, or other contingency or revised judgment requiring the gage to be reset to a particular slope and direction. A gage raised off the ground has less tendency for leaks to develop and to be discovered too late. Such a gage is not obstructed by growth of weeds, nor is it molested much by animals. It has less tendency to collect debris. In addition, the raised vertical gage is less subject to the effects of spattering, and with snow accumulated on the ground its further advantage is obvious.

G. L. Hayes (U. S. Forest Service, Roseburg, Ore.) and I. Kittredge (Department of Forestry, University of California, Berkeley 4, California, Authors' Closure)--Wilson's valued discussion raises several points upon which further comment may be justified. With him we regret that details of wind flows and direction were not available to aid in interpreting the rain gage results.

Regarding his question on how far the effects of a timber stand extend to gages down wind from its edge, it is true that "much of the rain came with southeast winds" (which paralleled the edge of the stand) but by no means all of it. Quoting from our paper, p. 96, "The rain-bearing winds which characteristically came from the southeast at the beginning of the storm, changing through south to west toward the end," and farther on in the same paragraph "Both intensities (of rain) and velocities (of wind) tend to increase with the amount of rain and in the later parts of the storm," therefore the periods of most intensive rainfall during those storms which contributed the most rain were typically accompanied by the strongest winds and these came from the southwesterly and westerly aspects which means the gages were down wind from the stand at such times. Had the stand influence extended beyond 34 ft for these statistically important storms it would have been reflected in the coefficients of variation in Figure 2. However, the distance to leeward to which a forest or shelterbelt oriented perpendicular to the direction of the rain-bearing winds may affect the catch of a gage would be greater than $3/4$ the height of the trees in many situations. Deficits of two to five per cent in catch at four times the height of the trees to leeward were recorded in England by HUDLESTON [1928]. The effects on wind velocity and on accumulation of snow may extend more than ten times the height to leeward.

Most of Wilson's discussion is devoted to pointing out the practical limitations of tilted orifice gages and to a defense of the conventionally installed gage having its unshielded orifice in horizontal placement. Seven issues are raised which will be discussed in order. First, however, it might be well to recognize that (a) the conventional rain gage will not catch from wind-borne rain a reliable sample of the fall to earth. This is adequately emphasized by the literature. Of the 147 articles annotated by BROOKS [1938], more than 60 discuss the inaccuracies in rain gaging that result from wind influences. KOSCHMEIDER'S [1934] experiments, which Wilson recognized as having control

gages as coming "nearest satisfying those who conceive of a true catch," showed that deficiencies in the catch of the conventional gage ranged from 11 per cent with a wind of nine miles per hour at gage height to 72 per cent with a wind of 36 mi/hr at gage height. (b) Such inaccuracies are intolerable for many scientific and research purposes in the fields of hydrology, ecology, forest fire control, and others, especially since improved catches can be obtained quite cheaply.

Keeping these points in mind the issues raised by Wilson will now be discussed.

(1) "True rainfall" may be an abstraction but in no way justifies the use of a deficient measurement of the fall when closer approximations can be obtained with reasonable time and expense. The objective in rain measurement is to obtain a fair sample of the fall reaching the Earth's surface for the area represented by the measurement. W. A. Rockie of the Soil Conservation Service reported in a paper before the Northwest Scientific Association at Spokane, Washington, in December 1936 that the rainfall collected by a large, shallow concrete runoff tank located on sloping ground near Pullman, Washington, had been reliably sampled by sloped orifice gages near its perimeter but deficiently sampled by horizontal orifice gages in similar positions. The runoff tank was large and shallow enough to simulate an integral part of the surrounding slope; its catch must have been very close to "true rainfall" for the immediate vicinity.

(2) The trough gage may cause some turbulence in the air stream above it, but due to the low velocities at four inches above the ground surface, and the presence of a grass cover mowed even with the top of the gage, turbulence induced by the gage should be negligible when compared to that caused by a gage and support extending 30 inches or more into the air stream.

(3) It is difficult to understand how "consistent and comparable results" can be obtained by the use of gages so subject to wind-caused inaccuracies as the conventional installation. Air velocities, raindrop size, and other factors, vary greatly but not consistently from place to place and from storm to storm.

(4) The areal sampling of precipitation is a separate problem. The admitted difficulties of reliable areal sampling in no way justify the use of unnecessarily biased gaging methods for spot measurements.

(5) The study under discussion concerned only the measurement of rain. Some of the installations used admittedly would be unsuitable for snow. At the same time, some of our findings may be suggestive for the measurement of snowfall because the difficulties arise in part from the same causes.

(6) It is granted that the wind at times approaches the ground from any and all directions in the turbulent air stream moving over a rough surface. The general movement, however, is parallel to the surface and from the prevailing direction. This is well demonstrated by the rime pattern on the windward side of instruments and other obstacles on mountain tops. But whether the air moves in laminar flow or turbulent flow, uphill or down, tilted gages should still catch a more representative sample of the rain falling to Earth than a vertical gage.

(7) For a large organization such as the Weather Bureau which operates numerous stations, frequently with unskilled observers, simplicity of installation and operation, and a minimum of maintenance undoubtedly have real value. But as pointed out earlier, for many scientific and research purposes first emphasis must be placed on accuracy. The practical difficulties enumerated are relatively less important than and must be subordinated to accuracy.

References

- BROOKS, C. F., Need for universal standards for measuring precipitation, snowfall, and snow cover, Trans. Intl. Comm. of Snow and of Glaciers, Assoc. Intl. Hydrol. Sci. Bull. 23, pp. 7-58, 1938.
HUDELESTON, F., Report on experiments with rain-gage shields and rain-gages under the lee of a high wood during the period 1st May 1928 to 30th April 1929, at Hutton John, Penrith, British Rainfall, v. 68, pp. 258-269, 1928.
KOSCHMEIDER, H., III Dansk Report, Methods and results of definite rain measurement, Mon. Wea. Rev., v. 62, pp. 5-7, 1934.

REPORT OF THE SPECIAL COMMITTEE ON THE GEOPHYSICAL AND
GEOLOGICAL STUDY OF THE CONTINENTS, 1948-1949

G. P. Woollard, Chairman

C. S. Beals
Francis Birch
Walter H. Bucher
Maurice Ewing
Roy W. Goranson
Ross Gunn
Sigmund I. Hammer

H. W. Hemple
Harry H. Hess
Patrick M. Hurley
Henry R. Josting
Chester R. Longwell
J. B. Macelwane
H. A. Marmar
Frank Neumann

B. Perkins, Jr.
E. B. Roberts
D. C. Skeels
Nelson C. Steenland
William T. Thom, Jr.
J. Tuzo Wilson
J. Lamar Worzel

World-wide gravity net--During the year 1948 there was considerable geological and geophysical activity both in this country and abroad having a direct bearing upon the study of the continents. Of general interest is the critical evaluation of the world's primary gravity base stations values by Morelli at the Geophysical Institute in Trieste, and Hirvonen at the Isostatic Institute in Helsinki. An actual check using an improved gravity meter was also attempted by the Chairman of the Committee working under the auspices of the Office of Naval Research and the Woods Hole Oceanographic Institution. The instrument used was a special Worden gravimeter having a range of 5400 mgal and a reading sensitivity of about 0.1 mgal. Approximately 82,000 mi were traveled in establishing one world-girdling loop and four lesser trans-oceanic loops. In all 165 stations were established and of these, 29 were reoccupation of old pendulum stations. Fourteen stations were national gravity base stations tied directly to Potsdam.

Closure for the world-girdling loop was 0.3 mgal and the average closure on all loops was 0.4 mgal. The median error using the mean of Morelli's and Hirvonen's adjusted pendulum values for the national pendulum base stations reoccupied, was found to be about 0.5 mgal. The total range in gravity covered by these measurements was 4200 mgal.

As part of the same program the relative change in gravity between the absolute gravity bases at the Bureau of Standards in Washington and the National Physical Laboratory at Teddington, England was measured. This was found to be 1096.5 mgal which is in agreement with the determination made in 1939 by Browne and Bullard using quartz pendulums. This interval indicates a five-mgal discrepancy between these two absolute determinations. Although Potsdam could not be reoccupied, the indirect ties through the national gravity bases indicate an error of about 18 mgal in the Potsdam absolute value. The track followed in these world wide measurements is shown in Figure 1.

Gravity work in North America--In the United States the United States Coast and Geodetic Survey established 50 new pendulum stations during 1948 which are the first such measurements made since before the War. These stations were located in Indiana, Kentucky, Kansas, Oklahoma, Colorado, Utah, Nevada, and New Mexico. The locations of these and previously established pendulum stations in the United States is shown in Figure 2. The Coast and Geodetic Survey also purchased a Worden gravimeter similar to the one used on the world-wide measurements and are now establishing a series of gravimeter and pendulum measurements in South America in cooperation with the Inter-American Geodetic Survey. In the west Kansas-Oklahoma area a regional gravity survey was made cooperatively between the United States Coast and Geodetic Survey and the United States Geological Survey using the Frost gravimeter of the Geological Survey. This investigation was part of the current departure of the vertical study now being conducted by the United States Coast and Geodetic Survey. In connection with this study many of the oil and exploration companies are cooperating by contributing regional data on an eight to ten mile station spacing, and although some of these data were given on a confidential basis for this particular study, it is hoped that all the data will be released for general scientific use in the not too distant future.

In view of the large accumulation of gravity data that is becoming available from various sources, the need for a national depository and institute to evaluate and adjust data to absolute datum as well

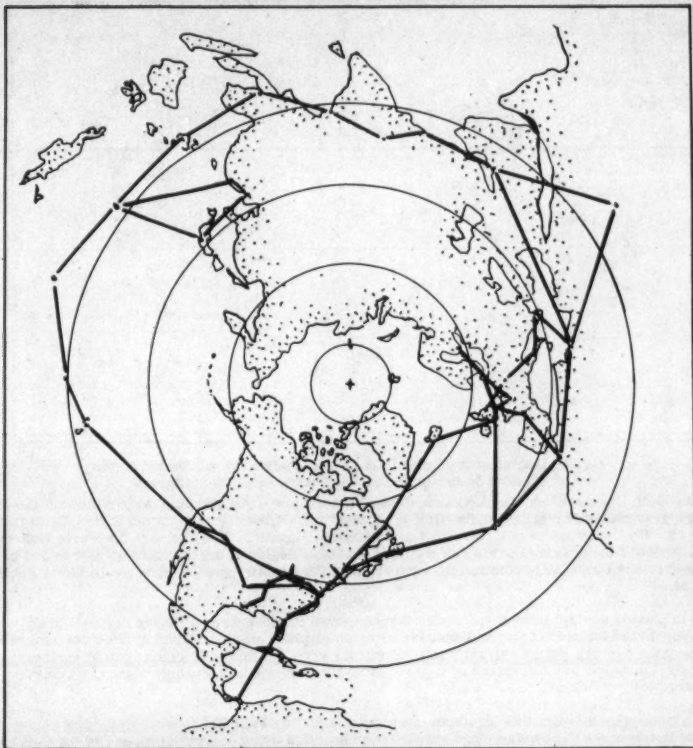


Fig. 1--World gravity measurement loops, 1948

as reduce the anomaly values and publish principal facts, is becoming greater each year. Although the United States Coast and Geodetic Survey would appear to be the logical group to do this, there are no funds at present to provide this service.

The regional gravity mapping program in the Eastern Seaboard which has been sponsored by the Geological Society of America and conducted on land by the Chairman of this Committee and off shore by Maurice Ewing and Lamar Worzel of Columbia University was further expanded this year. The land area covered now extends from the Gulf of St. Lawrence, with one traverse across Newfoundland, to the Gulf of Mexico, and from the Atlantic Coast to west of the Allegheny Front and the Adirondacks. At sea 12 off shore profiles across the Continental Shelf and several short profiles in the Bahama area have been established.

The above program has been supplemented by the extensive gravimeter work of the Dominion Observatory in eastern Canada, by regional data for the State of Florida and the Gulf Coast furnished by the Humble Oil and Refining Co., by the work of J. B. Hersey in Pennsylvania, by the survey of Lamar Worzel along the strike of the Appalachian Mountains, by the detailed investigations

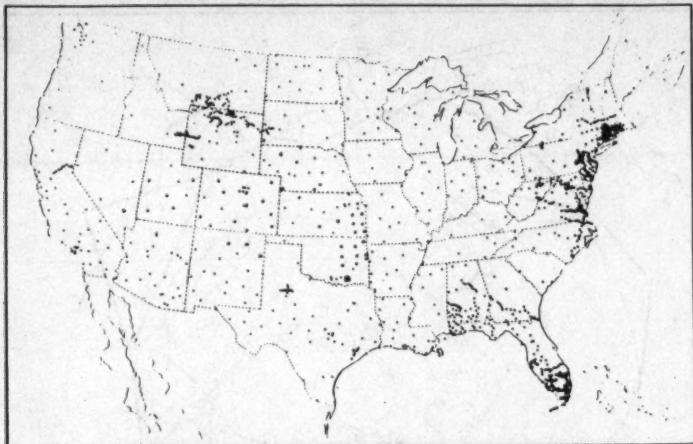


Fig. 2--Distribution of pendulum gravity stations in the United States established by the United States Coast and Geodetic Survey

of the Gulf Research and Development Company across the Appalachian Mountains and the off shore gravimeter traverses in the Gulf of Mexico established by the United States Geological Survey. The locations of all traverses are shown in Figure 3. In addition to the above studies it is understood the gravimeter work in the Cape Hatteras Region of the Standard Oil Group and that of the various cooperating companies in the Bahama Islands will soon be made available by publication.

In Canada the Dominion Observatory has continued its general program of regional gravity mapping in the interior of the back country using an airplane and in addition carried out extensive work in the Sudbury region. Gravity measurements were also made this past year in northern Canada, Labrador, and Greenland by a group from the University of Toronto using the Dominion Observatory pendulums.

Other gravity work that should be mentioned is that by Paul Wenschel of Columbia University in which traverses were established across South America using quartz pendulums of the Gulf Oil Co. and a Frost high-range gravimeter. These traverses were sponsored by the Office of Naval Research and the Inter-American Geodetic Commission as part of a program under which worldwide gravity observations were made in 1949. There already exists a series of off-shore gravity traverses along the western coast of South America which were established in 1947 by the group at Columbia University.

Gravity investigation planned for the summer of 1949 in the United States include (a) regional gravity survey of Colorado by Ralph Holmer of the Colorado School of Mines, on which the Shell Oil Company is cooperating by contributing regional data for those portions of the State they have surveyed; (b) a regional reconnaissance gravity survey of the northwest part of the country by the group at the University of Wisconsin to study the extent of the isostatically uncompensated tectonic province indicated by existing pendulum measurements of the United States Coast and Geodetic Survey; (c) some studies along the Rocky Mountain Front and in New England by Francis Birch of Harvard University. The general locations of the preliminary regional traverses planned in the northern part of the country which will tie to similar traverses in Canada are shown in Figure 4.

The program of the United States Coast and Geodetic Survey includes checks on some of the pendulum stations reported to be in gross error and the start of several regional traverses. In Canada, the Dominion Observatory plans to expand further their regional surveys using Atlas and

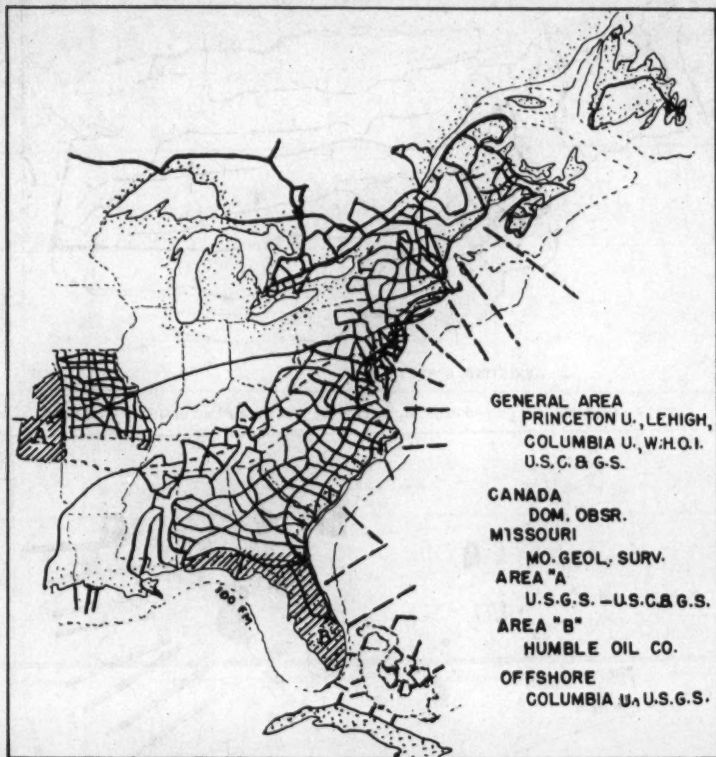


Fig. 3--Regional gravity surveys eastern seaboard North America
North American gravity meters.

At the time of writing (late spring, 1949) a series of gravity measurements is being made under the auspices of the Shell Oil Co. to study the crustal response to tidal forces. The program calls for simultaneous observations at 15 minute intervals over a two week period in various parts of the world.

Magnetic investigations in North America-- In the United States the most extensive magnetic investigations have been made using the airborne magnetometer. The United States Geological Survey program has been quite broad in scope and is best summarized by Figure 5 which shows work completed to date and investigations planned for the near future. In addition, in connection with the study of volcanoes, a series of measurements has been conducted ranging east-west from Bermuda to Bikini and north-south from the Aleutians to Mexico.

Although the large amount of commercial airborne magnetic work is essentially confidential, Aero Service Corporation published in the spring of 1949 an east-west traverse across the Mid-Continent region and the Fairchild Corporation ran a traverse from Lake Maricao, Venezuela

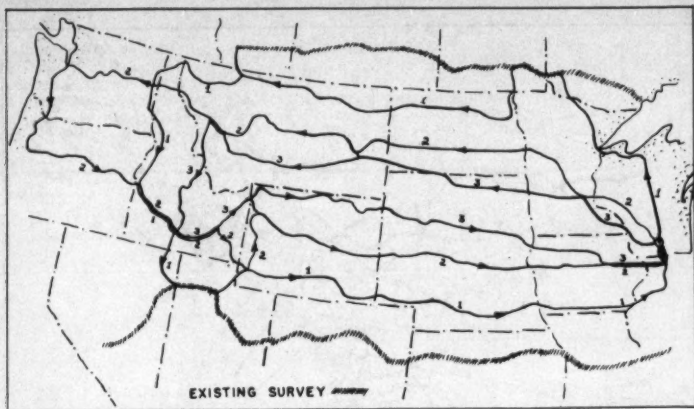


Fig. 4--Regional gravity and magnetic survey planned by the University of Wisconsin

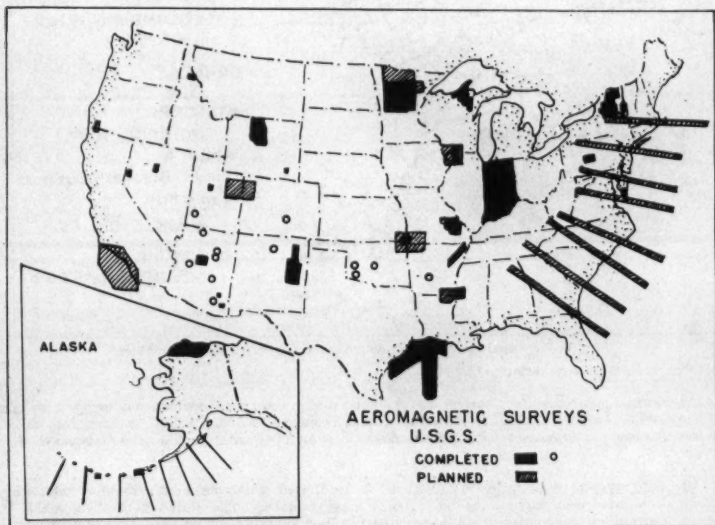


Fig. 5--Aeromagnetic surveys of the United States Geological Survey

across the Gulf of Mexico to Brownsville, Texas. This latter traverse was noteworthy for its complete lack of local change from Jamaica to Brownsville, the profile being essentially a smooth curve which appeared to correlate with the depth of water.

In Canada the Geological Survey has completed approximately 20,000 sq mi of airborne

magnetic surveys.

The land magnetic program of the United States Coast and Geodetic Survey, as well as that of the Dominion Observatory in Canada, includes the establishment of new primary base values and checks on old ones for secular variations. In addition, in Canada, vertical component measurements have been taken at most of the gravimeter stations established. In this country in connection with the gravimeter survey of the Eastern Seaboard vertical component measurements were also made at all gravity stations except in New England. Similar paired measurements are planned in connection with the regional gravity study of the northwest part of the country. In addition to the above the Dominion Observatory of Canada also established this past year a network of stations to study the location of the north magnetic pole.

Seismic investigations--Of general interest in connection with seismic studies of the crust are the results reported by MINTHROP [1949] from the Heligoland blast. These are summarized in Table 1.

Table 1--Seismic studies from the Heligoland blast

Velocity		Depth	Remarks
Longitudinal	Transverse		
km/sec	km/sec	km	
3.5	2.0	0.4	sediments solid
5.2	2.9	4-13	Granitic solid
6.5	3.6	...	Basaltic solid
8.1	4.5	...	Peridotite solid
9.2	5.6	57-110	? solid
7.0	?	110-118	? plastic
11.0	6.2	118-170	? solid
16.3	8.8	170-180	? solid
9.0	?	180-	alternately plastic and solid

Table 2--Seismic findings of the Department of Terrestrial Magnetism, Carnegie Institution of Washington

Velocity		Depth
Longitudinal	Transverse	
km/sec	km/sec	km
6.15 ± 0.1	3.5	0 - 12 ± 3
6.7 - 7.1		12 - 35
8.1		52 - 38

The investigations of crustal structure by the Department of Terrestrial Magnetism using large explosive charges, started in 1947, are continuing and were reported on at a series of papers at the 1946 Meeting of the Union. A summary of their findings in the Appalachian area of the eastern seaboard is given in Table 2. H. Tatel of the Department of Terrestrial Magnetism reports that there is evidence from the records of layering between 12 and 35 kms, and on the recording of shots traversing the Appalachian Mountains, there is a time delay in the arrivals suggesting a root beneath the mountains of about nine km.

Additional observations for the study of this particular feature are planned. In carrying out this program of crustal study, observations have also been made in New Mexico where the upper layer was found to have a velocity of 5.1 plus or minus 0.2 km/sec. The size of charges used varied from 500 - 2400 pounds of explosive. To date fourteen sets of observations have been made of which 11 were in the Appalachian area and three in New Mexico. It is of interest to note the extent to which cooperation has been obtained on this project. One of the papers presented at this year's meetings had 14 authors listed representing four different organizations not including the Navy or the TVA which cooperated on the blasting program.

In Canada the similar study being conducted by the Dominion Observatory using rock bursts in deep mines as a source of energy is continuing. A discontinuity at 36 km is reported and there is some evidence for another at 17 km.

In connection with older seismic studies of a similar nature the Office of Naval Research has recently advanced funds to L. B. Schlichter to work up the results of his investigations from quarry blasts in Massachusetts and Wisconsin.

At sea the deep reflection work reported by Hersey and Ewing (Woods Hole Oceanographic Institute and Columbia University) has indicated a discontinuity at about ten kilometers.



Fig. 6- Seismic refraction stations, Columbia University group

The off-shore seismic refraction studies over the continental shelf being conducted under Ewing at Columbia University and sponsored by the Geological Society of America were extended this past year by a traverse across the Gulf of Maine. The location of traverses established to date are shown in Figure 6. It is hoped that this study can be extended further to the south and that it will be possible to supplement it with oil-company data in the on shore areas. Similar studies are now also being made off the California Coast by Russell Raitt of the Marine Physical Laboratory at San Diego.

The cumulative plot of earthquakes epicenters in the United States started several years ago under the auspices of this Committee, has been continued and is shown in Figure 7. The persistence of earthquakes epicenters in what appears to be a fixed pattern of localities that are only partially related to known fault patterns within the Continent is quite striking and thought provoking.

Radioactive measurements in North America--In the United States, P. M. Hurley at M. I. T. is continuing his work on the radioactive age determinations of rocks under a grant from the Office of Naval Research. Of particular interest are the age relationships he has found, and in Table 3 a brief synopsis of results to date is shown. His results will be found reported in greater detail in Appendix A of this report (pp. 142-144).

Similar data prepared by J. Tuzo Wilson of the University of Toronto summarizing results for age determinations in Canada are given in Table 4.

Wilson in his paper, Recent Work in the Canadian Shield, pp. 101-114 of this issue of the Transactions, also calls attention to the zonal arrangement of radioactivity about the periphery of granitic

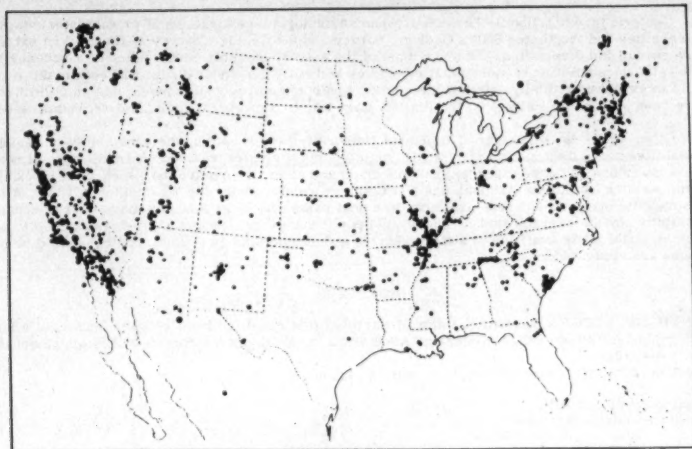


Fig. 7--Earthquake epicenters United States based on United States Coast and Geodetic Survey reports

Table 3--Radioactive age determinations of North American rocks

Location	Age
	my
East-west structures in Manitoba, Ontario, Quebec	2000
North-south structures in Northwest Territory and Manitoba	1300
East-west trends in Michigan and Ontario	1200
Northeast-southwest structures in Ontario (Algonquin Age)	1000
Northwest-southeast structure, Llano Co., Texas	1040
Northeast-southwest structure, Minnesota, Colorado, New Mexico	800
Northeast-southwest structures in Appalachian pre-Cambrian	800
Northeast-southwest structures in Adirondacks	500

Table 4--Radioactive age determinations of rocks in Canada [Wilson, 1948]

Location	Age
	my
Huron Claim, Manitoba (Keewatin)	1900
Great Bear Lake N. W. T. (Eldorado Mine)	1420
Wilberforce, Ont. (Grenville)	1050
Conger top, Ont. (Grenville)	1050
Pied des Monts, Ont. (Grenville)	900
Besner Twp. Ont. (Grenville)	760-820

batholiths in Canada. In some cases the peripheral area has the highest activity; in others the highest activity is in central zones. This criterion might therefore serve to identify whether the exposure represents an upper surface, or a truncated deeper section of the intrusive.

Thermal measurements--The thermal gradient measurements on which Francis Birch of Harvard University reported at the AGU Meeting of 1948 are being continued. In Canada similar measurements are being made in deep mines by Misener of Toronto University. The measurements in Canada will give an accurate measurement of the thermal gradient down to 7200 ft for some localities.

Geologic investigations--The comprehensive geologic investigations of private interests, the universities and the United States Geologic Survey and the Geologic Survey of Canada are extremely wide spread and diversified. Although most of the country has only been studied on a reconnaissance basis, the accumulation of more detailed studies and more geophysical data will soon make it possible to examine critically existing ideas on orogenic and epigenetic movements which hitherto have been predicated entirely on the limited story told by superficial geological reconnaissance.

Other work--W. H. Bucher of Columbia University has brought up the desirability of having the Committee serve as a clearing house for obtaining and having reproduced on small scale at nominal costs (sufficient to cover expenses) various maps and other descriptive data such as were exhibited at the Meeting of the International Union of Geodesy and Geophysics in Washington in 1939. Although this specific material has been available on a cost basis, the large size has made their purchase prohibitive by the average student who would benefit most from the material. It is planned to have such material made available in a reduced size, and suggestions as to material that should be included are requested.

References

- MINTHROP, LUDGER, On stratification of Earth's crust resulting from seismic studies of a large explosion and of great earthquakes, *Abst. from the St. Louis meeting, Soc. Explor. Geophys.*, p. 44, 1949.
 WILSON, J. TUZO, *Canadian Geophys. Bull.*, v. 11, no. 3, p. 37, 1948.

Department of Geology,
 University of Wisconsin,
 Madison, Wisconsin

(Manuscript received July 22, 1949; presented by title at the Thirtieth Annual Meeting, Washington, D. C., April 22, 1949; open for formal discussion until July 1, 1950.)

APPENDIX A--PROGRESS REPORT ON AGE MEASUREMENTS

Patrick M. Hurley

Age measurements on the Pre-Cambrian rocks of this continent are continuing to appear at a slow rate, with finally a small amount of order becoming apparent. However, the seeming regularities may well be entirely the result of a desire to bring some order into the picture on the part of the writer rather than the regularities actually existing. It is with fear and trembling that any helium age is reported at this time, since there are still unresolved anomalies in the art of helium age measurement. Certainly all the values reported will be changed by at least a minor amount as better evaluations are made of gangue mineral contamination, and accuracy is increased by repeated measurements.

In general, the measurements support the hypothesis that areas of the continental mass have been subjected to stresses from different directions at different times; and that the history of a Pre-Cambrian area is best preserved by sets of major structures which have persistent directions and probably represent the roots of old mountain belts. The time of these ancient orogenies is assumed to be given by pegmatites or lower temperature mineralizations located within them, although the danger in this assumption is becoming increasingly apparent.

A correlation of age measurements with direction of structural trends in the host environment shows a degree of relationship which is encouraging. From oldest to youngest, the groups of age measurements are as follows:

(1) East-west trending structures in Manitoba, Ontario, and Quebec

Southeastern Manitoba	Pb/U	2000 my
Southeastern Manitoba	Pb/Th	2000 my
Southeastern Manitoba	Pb/U	1950 my
Southeastern Manitoba	Sr/Rb	2100 my
Southeastern Manitoba	Sr/Rb	2200 my
Southeastern Manitoba	Sr/Rb	2350 my
Southeastern Manitoba	Sr/Rb	2300 my
Larder Lake, Ont.	magnetite-hellum	2100 my
Larder Lake, Ont.	magnetite-hellum	2400 my
Noranda, Quebec	magnetite-hellum	2000 my

(2) North-south trending structures in Northwest Territories, Manitoba, and South Dakota

Great Bear Lake	Pb/U	1400 my
Lake Athabasca	Pb/U	1300 my
Bird River Gabbro, Manitoba	magnetite-helium	1300 my
Black Hills, South Dakota	Pb/U	1350 my

(3) East-west and variable trends in Michigan and southern Ontario represented by metamorphism of iron ranges in Michigan, and older gabbro emplacement in Ontario

Michigamme, Mich.	magnetite-helium	1200 my
Champion, Mich.	magnetite-helium	1350 my
Republic, Mich.	magnetite-helium	1200 my
Humboldt, Mich.	magnetite-helium	1600 my
Edwards, Mich.	magnetite-helium	1200 my
Edwards, Mich.	magnetite-helium	1500 my
Edwards, Mich.	magnetite-helium	1250 my
Ironwood, Mich.	pyrite-helium	1100 my
Dungannon, Ont., older gabbro	magnetite-helium	1400 my
Hart Co., Ont. gabbro	magnetite-helium	1300 my

(4) Northeast-southwest structures and dominant granite emplacement in southern Ontario and Quebec of so-called Algonian age

Wilberforce, Ont.	Pb/U	1050 my
Pieds des Monts, Que.	Pb/U	900 my
Villeneuve, Que.	Pb/U	1020 my
Besner Mine, Henvey Twp., Ont.	Pb/U	800 my

(5) Northwest-southeast structure, Llano Co., Texas

Llano Co.	magnetite-helium	1050 my
Baringer Hill	Pb/U	1040 my

(6) Northeast-southwest trends from Vermilion range in Minnesota, through Colorado and New Mexico

Vermilion Batholith, Minn.	magnetite-helium	750 my
Giant's Range Granite, Minn.	magnetite-helium	800 my
Brown Derby, Colo.	Sr/Rb	900 my
Brown Derby, Colo.	Sr/Rb	800 my
Dixon, N. M.	Sr/Rb	800 my
Glorietta Monazite, N. M.	Pb/Th	860 my
Silver Plume Granite, Colo.	cerite	870 my
Bull Creek, N. Mex., Monazite	Pb/Th	800 my

(7) Northeast-southwest structures in southern Appalachian Pre-Cambrian exposures

Cranberry, N. C.	magnetite-helium	800 my
Cranberry, N. C.	magnetite-helium	750 my
Amherst Co., Va.	Pb/Th	800 my
Mars Hill, N. C.	Pb/Th	600 my
Spruce Pine, N. C.	Pb/Th	600 my

(8) Northeast-southwest and variable structures in New Jersey Highlands and Adirondacks

Franklin Furnace, N. J.	magnetite-helium	530 my
Ford, N. J.	magnetite-helium	550 my
Salisbury, N. Y.	magnetite-helium	540 my
Salisbury, N. Y.	magnetite-helium	500 my
Lyon Mt., N. Y.	magnetite-helium	590 my
Jayville, N. Y.	magnetite-helium	450 my
Jayville, N. Y.	magnetite-helium	725 my
Benson, N. Y.	magnetite-helium	650 my
Benson, N. Y.	magnetite-helium	1500 my

The corrected values for the lead measurements in Manitoba were given by Arthur Holmes in the Report of the Committee on Measurement of Geologic Time of the National Research Council for 1946-1947. Various annual reports of the same committee contain data on the following measurements listed: Lake Athabaska [HECHT and KROUPA, 1936, p. 60]; Glorietta, N. Mex. [MUENCH, 1937, p. 82]; Bull Creek, N. Mex. [MUENCH, 1939, p. 90]; and Mars Hill, N. C. [KROUPA, 1937, p. 58]. Some of these have been corrected for common lead by Holmes. Strontium-rubidium measurements were made by L. H. Ahrens and reported in the Bulletin of the Geological Society of America, v. 60, p. 217, 1949. The Great Bear Lake, Wilberforce, Pieds des Monts, and Besner lead ratios were given by Nier in the Physical Review, v. 55, no. 2, p. 153, 1939. The original Black Hills, Villeneuve, and Baringer Hill measurements were reported in the National Research Council Bulletin 80, Physics of the Earth IV, 1931, and corrected for common lead by Holmes. The age of the Amherst Co. allanite was reported by Marble in the American Journal of Science, v. 30, p. 349, 1935; and the Spruce Pine, N. C. monazite by Bliss in the same journal, v. 242, p. 327, 1944. The helium measurements were made at Massachusetts Institute of Technology by P. M. Hurley, supported by the Office of Naval Research in a laboratory established under a grant from the Geological Society of America.

Massachusetts Institute of Technology,
Cambridge, Massachusetts

(Communicated manuscript received April 4, 1949, related to the Report of the Special Committee on the Geophysical and Geological Study of the Continents, presented by title at the Thirtieth Annual Meeting, April 22, 1949; open for formal discussion until July 1, 1950.)

American Standards Association--The latest approved standard is as follows:

Z38-8-6-1949, American standard of practice for photographic processing manipulation of paper. This standard applies to operations concerning the processing of photographic paper involving developing, rinsing, fixing, washing, and drying.

Fred Anderegg
AGU Representative on ASA Committee
on Photography Z38

BIBLIOGRAPHY

BIBLIOGRAPHY: GENERAL

- BARTELS, J., Mathematical methods in geophysics, *FIAT Rev. German Sci.* (1939-1946) Applied mathematics, pt V (Off. Mil. Govt. Germany), pp. 89-99, 1948 (in German) [abstr. in *Phys. Abstr.*, v. 52, no. 623, p. 793, 1949].
- FARRAR, R. L., Jr., and CADY, G. H., Comparison of age with the relative abundance of argon and potassium in rocks, *J. Amer. Chem. Soc.*, v. 71, pp. 742-743, 1949 [abstr. in *Phys. Abstr.*, v. 52, no. 623, p. 795, 1949].
- JEFFREYS, H., The origin of the solar system, *Mon. Not. R. Astr. Soc.*, v. 108, no. 1, pp. 94-103, 1948 [abstr. in *Phys. Abstr.*, v. 52, no. 623, p. 713, 1949].
- LÓPEZ de AZCONA, JUAN M., Geophysical interpretation of the isotopic values of the common leads, *Rev. Real. Acad. Cienc.*, Madrid, v. 42, pp. 393-420, 1948 [abstr. in *Chem. Abstr.*, v. 43, no. 21, p. 8322, 1949].
- ROURE, H., New theory of the solar planetary system, *C.-R. Acad. Sci.*, Paris, v. 223, pp. 885-887, 1946 (in French) [abstr. in *Phys. Abstr.*, v. 52, no. 623, p. 713, 1949].
- ROURE, H., New theory of the major planets of the solar system, *Bull. Astr.*, Paris, v. 15, no. 1, pp. 1-74, 1949 (in French) [abstr. in *Phys. Abstr.*, v. 52, no. 623, p. 712, 1949].
- SCHWINNER, ROBERT, Mountain formation, magmatic cycles, and ore deposits in the eastern Alps, *Berg hüttenmänn. Monatsh. montan. Hochschule Leoben*, v. 94, pp. 134-143, 1949 [abstr. in *Chem. Abstr.*, v. 43, no. 21, p. 8314, 1949].
- SCHWINNER, R. S. B., The large-scale fields of the Earth's crust considered as Bénard-turbulence cells, *S. B. Ost Akad. Wiss.*, pt. 2a, v. 156, no. 7-8, pp. 441-455, 1948 (in German) [abstr. in *Phys. Abstr.*, v. 52, no. 623, p. 795, 1949].
- WALTERS, R. C. S., Some geophysical experiences in water supply, *J. Soc. Water Engrs.*, v. 3, pp. 436-441, 1949 [abstr. in *Chem. Abstr.*, v. 43, no. 22, p. 9301, 1949].
- ZAHRADNÍČEK, J., Form and mass of the Earth, *Publ. Fac. Sci. Univ. Masaryk (Sp. Prir. Fak. Masaryk Univ.)*, no. 286, 16 pp., 1947 [abstr. in *Appl. Mech. Rev.*, v. 2, no. 12, p. 279, 1949].

BIBLIOGRAPHY: GEODESY

- BERROTH, A., Das Fundamentalsystem der Schwere im Lichte neuer Reversionspendelmessungen, *Bull. Géod.*, no. 12, pp. 183-204, 1949.
- BULLARD, E. C., The figure of the Earth, *Mon. Not. R. Astr. Soc.*, *Geophys. Suppl.*, v. 5, pp. 186-192, 1948 [abstr. in *Phys. Abstr.*, v. 52, p. 540, 1949].
- CATTALA, R. R. L., Etudes gravimétriques à Madagascar, *Bull. Géol. Madagascar*, v. 1, pp. 75-87, 1949.
- EVANS, P., and COATES, J., Geophysical prospecting for oil in India, *Indian Minerals*, v. 2, pp. 92-102, 1948 [abstr. in *Chem. Abstr.*, v. 43, no. 22, p. 8992, 1949].
- GULATÉE, B. L., Topographic-isostatic effect of outer Hayford zones, *Bull. Géod.*, no. 12, pp. 180-182, 1949.
- GUTENBERG, B., Isostasy and its meaning, *Tellus*, v. 1, pp. 1-5, 1949.
- HEISKANEN, W., and SALA, I., The topographic-isostatic reduction of gravity anomalies by the aid of small scale maps, *Ann. Acad. Sci. Fenn.*, Helsinki, Ser. 3A, III, 23 pp., 1949.
- INOUE, W., On the relation between gravity anomalies and the subterranean structure, *Geophys. Mag.*, Tokyo, v. 16, no. 2, pp. 57-63, 1948.
- JEFFREYS, HAROLD, On the absolute measurement of gravity, *Mon. Not. R. Astron. Soc.*, *Geophys. Suppl.*, v. 5, pp. 398-408, 1949.
- LEJAY, R. P., Comptes rendus des séances de travail de la Section de Gravimétrie de l'Association Internationale de Géodésie (includes nine supplements by various authors relating to work in several regions), *Bull. Géod.*, no. 12, pp. 119-169, 1949 (in French and English).
- LINK, F., and BOHM, J., Variétés géodétiques, *Zeměměřický Obzor Sls*, Prague, v. 37, no. 9, pp. 118-119, 1949 (in Czechoslovakian).
- REGOČZI, EMIL, La mensuration cadastrale en Hongrie, *Zeměměřický Obzor Sls*, Prague, v. 37, no. 9, pp. 109-115, 1949 (in Czechoslovakian).
- RICH, S. R., and ROSEN, A. H., Sonic navigation system, *Electronics*, v. 21, pp. 92-97, 1948 [abstr. in *Phys. Abstr.*, v. 52, p. 559, 1949].
- TANNI, L., The regional rise of the geoid in Central Europe, *Ann. Acad. Sci. Fenn.*, Helsinki, Ser. 3A, III, 19 pp., 1949.
- VENING MEINESZ, F. A., The isostatic reduction and the indirect or Bowie effect, *Bull. Géod.*, no. 12, pp. 170-179, 1949.
- WOLF, HELMUT, Die Stellung des Boltzschens Entwicklungs-Verfahrens in der Ausgleichsrechnung, *Inst. für Erdmessung, Bamberg*, pp. 11-52, 1949 (in German with summary in English).
- WOLF, HELMUT, Papers on various aspects of geodesy, *Inst. für Erdmessung, Bamberg*, 143 pp., 1949 (in German with summaries in English).

BIBLIOGRAPHY: SEISMOLOGY

- ALTENBURG, K., Dispersion of longitudinal earthquake waves, *Experientia*, v. 5, p. 68, 1949 (in German) [abstr. in *Phys. Abstr.*, v. 52, no. 623, p. 794, 1949].
- HARDTWIG, E., On the increase of the period of seismic waves, *Geofis. Pura Appl.*, v. 13, pp. 75-87, 1948 (in German) [abstr. in *Phys. Abstr.*, v. 52, no. 623, p. 794, 1949].

- HIRONA, T., Mathematical theory on shallow earthquake, *Geophys. Mag.*, Tokyo, v. 18, 116 pp., 1948; v. 21, 97 pp., 1949.
- MORITA, M., On seismic waves at large distances, a study of the north Chilean earthquake of February 23, 1933, pt. 2, Waves of P' Group, *Geophys. Mag.*, Tokyo, v. 17, pp. 37-63, 1948.
- WILLMORE, P. L., Seismic experiments on the North German explosions, 1946 to 1947, *Philos. Trans. A*, no. 843, pp. 123-151, 1949 [abstr. in *Phys. Abstr.*, v. 52, no. 623, p. 793, 1949].

BIBLIOGRAPHY: METEOROLOGY

- ABILD, BRUNO, Der Strahlungsfehler bei der Graw'schen Wettersonde, *Ann. Met.*, Hamburg, v. 2, no. 1 and 2, pp. 28-29, 1949 (summary in English).
- AUSTIN, JAMES M., Temperature advection and pressure changes, *J. Met.*, v. 6, pp. 358-360, 1949.
- BANNON, J. K., Large-scale vertical motion in the atmosphere, *Nat.*, London, v. 163, pp. 495-496, 1949 [abstr. in *Phys. Abstr.*, v. 52, no. 623, p. 796, 1949].
- BANNON, J. K., The angular deviation of the wind from the isobars, at Liverpool, *J. R. Met. Soc.*, v. 75, pp. 131-146, 1949.
- BECKEN, FRIEDRICH W., Sturmfluten und Regenmengen in Cuxhaven, *Ann. Met.*, Hamburg, v. 2, no. 1 and 2, pp. 51-53, 1949 (summary in English).
- BECKER, RICHARD, Der planetarische Jahresgang der maritim-subtropischen Hochdruckkerne, *Ann. Met.*, Hamburg, v. 2, no. 1 and 2, pp. 48-51, 1949 (summary in English).
- BERG, HELLMUT, Die Globalstrahlung in Westdeutschland, *Ann. Met.*, Hamburg, v. 2, no. 1 and 2, pp. 30-35, 1949 (summary in English).
- BLECK, GERHARD, Ein Beitrag zur Trajektorientheorie, *Ann. Met.*, Hamburg, v. 2, no. 3 and 4, pp. 96-99, 1949 (summary in English).
- BONDI, H., The growth of meteorological disturbances, *Proc. Camb. Phil. Soc.*, v. 45, pt. 1, pp. 92-98, 1949 [abstr. in *Phys. Abstr.*, v. 52, no. 620, p. 527, 1949].
- CALDER, K. L., The criterion of turbulence in a fluid of variable density with particular reference to conditions in the atmosphere, *J. R. Met. Soc.*, v. 75, pp. 71-88, 1949.
- CHAKRAVORTY, K. C., Aviation Weather Risks at Delhi, *India Met. Dept., Sci. Notes*, v. 10, pp. 221-241 + 1 pl., 1949.
- CHARNEY, J. G., and ELIASSEN, A., A numerical method for predicting the perturbations of the middle latitude westerlies, *Tellus*, v. 1, pp. 38-54, 1948 [abstr. in *Phys. Abstr.*, v. 52, no. 621, p. 627, 1949].
- COX, E. F.; ATANASOFF, J. V.; SNAVELY, B. L.; BEECHER, D. W.; and BROWN, J., Upper-atmosphere temperatures from Helgoland Big Bang, *J. Met.*, v. 6, pp. 300-311, 1949.
- CRADDOCK, J. M., The development of cumulus cloud, results of observations made in Malaya, *J. R. Met. Soc.*, v. 75, pp. 147-153 + 2 pl., 1949.
- CROCKER, A. M., Synoptic applications of the frontal contour chart: the motion of selected lows, 5-7 November, 1946, *J. R. Met. Soc.*, v. 75, pp. 57-70, 1949.
- D'ALBE FOURNIER, E. M., Some experiments on the condensation of water vapour at temperatures below 0°C, *J. R. Met. Soc.*, v. 75, pp. 1-14, 1949.
- SEKERA, ZDENEK, The distribution of kinetic energy in certain types of steady barotropic currents, *J. Met.*, v. 6, pp. 321-329, 1949.
- STARRETT, LOYD G., The relation of precipitation patterns in North America to certain types of jet streams at the 300-millibar level, *J. Met.*, v. 6, pp. 347-352, 1949.
- TAIT, G. W. C., The vertical temperature gradient in the lower atmosphere under daylight conditions, *J. R. Met. Soc.*, v. 75, pp. 287-292, 1949.
- TEWELES, SIDNEY, JR., The tentative normal diurnal height change of the 700-millibar surface over the United States and adjacent areas, *Mon. Wea. Rev.*, v. 77, pp. 167-175, 1949.
- ULRICH, KARL O., Statistische Untersuchung des Strahlungsfehlers der Graw'schen Wettersonde, *Ann. Met.*, Hamburg, v. 2, no. 1 and 2, pp. 25-28, 1949 (summary in English).
- VAN MIEGHEM, JACQUES, La stabilité des mouvements atmosphériques, *Organ. Met. Internationale*, 9 pp., 1948.
- VAN MIEGHEM, J., Les équations générales de la mécanique et de l'énergétique des milieux turbulents en vue des applications à la météorologie, *Inst. R. Met. Belgique*, v. 34, 60 pp., 1949.
- VILLENEUVE, G. OSCAR, La météorologie, aperçu historique (Meteorology; a historic review), *Bur. Mét., Quebec, Bull.*, no. 11, pp. 131-176, 1948.
- VILLENEUVE, G. OSCAR, La météorologie, sa nécessité, *Bur. Mét., Quebec, Bull.*, no. 14, 9 pp., 1949.
- WALDEN, HANS, 25-tägiger Zyklus tiefen Luftdrucks im südlichen Nordmeer, November 1947 bis Dezember 1948, *Ann. Met.*, Hamburg, v. 2, pp. 79-85, 1949 (summary in English).
- WEICKMANN, LUDWIG (Ed), Der heiße und trockene Sommer 1947, *Ber. Deutschen Wetterdienstes*, US Zone, Bad Kissingen, no. 7, 51 pp., 1949.
- WHITE, ROBERT M., The role of mountains in the angular-momentum balance of the atmosphere, *J. Met.*, v. 6, pp. 353-355, 1949.
- WIDGER, WILLIAM K., JR., A study of the flow of angular momentum in the atmosphere, *J. Met.*, v. 6, pp. 291-299, 1949.

BIBLIOGRAPHY: TERRESTRIAL MAGNETISM AND ELECTRICITY

- FRITSCH, V., Einige Untersuchungen an Blitzschutzerdungen, *Bull. SEV*, Zürich, v. 40, no. 11, pp. 354-359, 1949.
- HATAKEYAMA, H., The electric charge neutralized by the lightning discharge, *J. Geomagnetism and Geoelectricity*, Kyoto, v. 1, no. 1, pp. 4-6, 1949.

- IMAMITI, S., Characteristics of geomagnetic diurnal variation at Kakioka, *J. Geomagnetism and Geoelectricity*, Kyoto, v. 1, no. 1, pp. 12-13, 1949.
- KATO, YOSHIO, On the new theory of the magnetic storm, *Geophys.*, Tohoku Univ., Japan, v. 1, no. 1, pp. 23-39, 1949.
- KATO, YOSHIO, and SHOJI, RIKI, New type of the Earth inductor and its use for the prospecting of the underground structure, *Geophys.*, Tohoku Univ., Japan, v. 1, no. 1, pp. 50-52, 1949.
- KATO, YOSHIO, and UTASHIRO, SHINKICHI, On the changes of the terrestrial magnetic field accompanying the great Nankaido earthquake of 1946, *Geophys.*, Tohoku Univ., Japan, v. 1, no. 1, pp. 40-41, 1949.
- KIMPARA, A., The wave form of atmospheric in day time, *J. Geomagnetism and Geoelectricity*, Kyoto, v. 1, no. 1, pp. 14-16, 1949.
- MATSUSHITA, S., On the semi-diurnal lunar tide (M_2) in region F, *J. Geomagnetism and Geoelectricity*, Kyoto, v. 1, no. 1, pp. 17-21, 1949.
- NAGATA, T., Southward shifting of the auroral zone accompanying the growth of a magnetic storm, *J. Geomagnetism and Geoelectricity*, Kyoto, v. 1, no. 1, pp. 7-9, 1949.
- OLCZAK, T., Situation actuelle de l'organisation des études sur le magnétisme terrestre en Pologne, *Polish Geol. Mag.*, Warsaw, v. 4, pp. 268-273, 1949 (in Polish with summary in French).
- TAMURA, Y., On the distribution of electricity in thunderclouds, *J. Geomagnetism and Geoelectricity*, Kyoto, v. 1, no. 1, pp. 22-25, 1949.
- TSUBOKAWA, I., A new type magnetometer (the G.S.B. type magnetometer), *J. Geomagnetism and Geoelectricity*, Kyoto, v. 1, no. 1, pp. 10-11, 1949.
- YONEZAWA, T., On the fluctuation in electron density of the F_2 layer of the ionosphere, *J. Geomagnetism and Geoelectricity*, Kyoto, v. 1, no. 1, pp. 26-30, 1949.
- YOSHIMATSU, T., Secular variation of Earth-current potentials, *J. Geomagnetism and Geoelectricity*, Kyoto, v. 1, no. 1, pp. 31-33, 1949.

BIBLIOGRAPHY: OCEANOGRAPHY

- ASHTON, E. W. S., and O'SULLIVAN, J. K., Effect of rain in calming the sea, *Nature*, v. 164, pp. 320-321, 1949.
- BASSINDALE, R. F.; EBLING, F. J.; KITCHING, J. A.; and PURCHON, R. D., The ecology of the Lough Ine Rapids with special reference to water currents, *J. Ecology*, v. 36, pp. 305-322, 1948.
- BERGSTEIN, F., Method of determining the effect of wind on sea level, and its application to computation of land elevation, *Stat. Met.-Hydrog. Anst. Medd.*, Ser. Uppsater, no. 49, 22 pp., 1945 (in Swedish).
- BONNET, L., and LAMOEN, J., Model experiments on the Belgian ports of the North Sea, *Dock Harb. Auth.*, v. 30, pp. 169-174, 201-205, 237-243, 1949.
- DEACON, G. E. R., Waves and swell, *J. R. Met. Soc.*, v. 75, pp. 227-238, 1949.
- DEFANT, A., Das Phänomen der Scylla und Charybdis in der Strasse von Messina, *Naturwiss.*, pp. 729-734, 1940.
- DEFANT, A., Scilla e Cariddi e le correnti di mare nello Stretto di Messina, *Geofis. Pura Appl.*, v. 11, no. 2, 20 pp., 1940.
- DEUTSCHES HYDROGRAPHISCHES INSTITUT, Jahresberichte, Hamburg, No. 1, 1946, 64 pp., 12 pl., 1947; No. 2, 1947, 67 pp., 13 pl., 1948; No. 3, 1948, 66 pp., 8 maps, 4 pl., 1949. (Published in German and in English).
- DOODSON, A. T. (Director), Liverpool Observatory and Tidal Institute, Annual reports, Liverpool, Centenary and 1940-1945, 28 pp., 1945; 1946, 14 pp., 4 fig., 1946; 1947, 11 pp., 1948, 11 pp., 1948.
- GHEORGHIU, V. G., and CALINICENCO, N., Etude sur la variation de la conductibilité électrique de l'eau de la Mer Noire avec la température et son emploi à la mesure de la température de l'eau marine, *Ann. Sci.*, Univ. Jassy, Sec. 2, v. 26, pp. 3-18, 1940.
- HARE, F. K., and MONTGOMERY, M. R., Ice, open water, and winter climate in the eastern Arctic of North America, *Arctic*, v. 2, pp. 79-89, 1949.
- HORTON, D. F., Shore effects of coastal structures, *Mil. Eng.*, v. 40, pp. 402-405, 1948.
- JACOBSON, A. W., An instrument for recording continuously the salinity, temperature, and depth of water, *Trans. Amer. Inst. Elect. Eng.*, v. 67, pp. 714-722, 1948.
- KIERNAN, E. F., Telemetering fathometer, *Electronics*, v. 20, no. 10, pp. 96-98, Oct. 1947.
- KIRK, T. H., Observing weather at sea; II, sea surface temperature, *Mar. Obs.*, v. 17, pp. 100-102, 1947.
- LADD, H. S., The value of marine bottom samples, *J. Coast and Geodetic Survey*, no. 1, pp. 83-84, 1948.
- LAMONT, A. H., Ice conditions over Hudson Bay and related weather phenomena, *Bull. Amer. Met. Soc.*, v. 30, pp. 288-289, 1949.
- LOWELL, S. C., The propagation of waves in shallow water, *Comm. Appl. Math.*, v. 2, pp. 275-291, 1949.
- MINKIN, R. R., Coast protection; a survey of beach stability, *Dock Harb. Auth.*, v. 29, pp. 165-169, 193-198, 232-236, 251-256, 281-285, 311-314, 1948-1949.
- NEUMANN, G., Freie Schwingungen (Seiches) der Putziger Wiek, *Ann. Hydrographie*, v. 72, pp. 225-235, 1944.
- PETTERSSON, HANS, The floor of the ocean, *Endeavour*, v. 8, pp. 182-187, 1949.
- POLLI, SILVIO, L'oscillazione annua del Mare Mediterraneo, *Arch. Ocean. Limnologia*, v. 1, pp. 22-30, 1941.
- POTTS, C. B., Precision echo sounding in hydrography, *Canad. Surveyor*, v. 10, no. 2, pp. 1-10, 1949.
- SHEPARD, F. P., Terrestrial topography of submarine canyons revealed by diving, *Bull. Geol. Soc.*

Amer., v. 60, pp. 1597-1612, 1949.

TOLSTOY, I., and EWING, M., North Atlantic hydrography and the Mid-Atlantic Ridge, *Bull. Geol. Soc. Amer.*, v. 60, pp. 1527-1540, 1949.

WISEMAN, J. D. H., Geology of the deep sea floor, *Nature*, v. 184, pp. 682-684, 1949.

BIBLIOGRAPHY: VOLCANOLOGY

ABANASEV, G. D., Comparison of intrusive complexes in various parts of the S.S.S.R., *Izvest. Akad. Nauk S.S.S.R., Ser. Geol.*, no. 4, pp. 3-18, 1949.

ASLANYAN, A. T., On the age of effusive quartz porphyries of the Lower Caucasus, *Izv. Akad. Nauk S.S.S.R.*, no. 5, pp. 141-144, 1949.

BELYANKIN, D. S., Magmatic liqation, *Izv. Akad. Nauk S.S.S.R., Ser. Geol.*, no. 5, pp. 35-39, 1949.

BETEKTIN, A. G., On the genesis of ore minerals, *Zap. Vses. Min. Obsch.*, v. 78, pp. 177-181, 1949.

BROUWER, H. A., Sur un massif granodioritique et ses phénomènes de contact à l'ouest de Palapa (Célebes), *Kon. Neder. Akad. Wet.*, v. 52, pp. 610-613, 1949.

EREMEEV, V. P., On characteristic intrusions of Central Tuvi, *Dokl. Akad. Nauk S.S.S.R.*, v. 67, pp. 543-545, 1949. [Gives mode, chemical analyses, and variation diagram for five intrusive rocks.]

FAVORSKAYA, M. A., Tertiary tuffs of the Southern Shore (of the Black Sea), *Izv. Akad. Nauk S.S.S.R.*, no. 5, pp. 137-141, 1949.

GONZALEZ-BONORINO, FELIX, Diferenciación magmática y alteración hidrotermal en Agua Tapada, *Rev. Asoc. Geol. Arg.*, v. 4, pp. 181-217, 1949.

GUIGUES, J., and LAPLAINE, L., Note sur quelques granites de la région de Tananarive, *Bull. Géol. Madagascar*, v. 1, pp. 12-19, 1949.

GUIMARAES, D., La genèse des orthopyroxènes, *Bull. Soc. Géol. France*, v. 18 (5), pp. 645-662, 1948.

HEIM, R. C., Petrology of the Mt. Aigoual Area in the southeastern Cevennes, France, *Kon. Neder. Akad. Wet.*, v. 52, pp. 676-684, 1949.

HIEKE, O., Sulla presenza di basalti limburgitici nell'Africa Orientale, *Atti Accad. Naz. Lincei*, v. 5, pp. 70-77, 1948.

HUNTING, MARSHALL T., Perlite and other volcanic glass occurrences in Washington, *Wash. State Div. Min. Geol. Olympia, Rep. Inv. No. 17*, 77 pp., 1949.

KRUPICKA, J., Petrological studies from the northeastern part of the Central Bohemian Pluton, *Stornik Stat. Geol. vst. Rep. Českoslov.*, v. 15, pp. 259-388, 1948.

KUSHAREV, I. P., On the detection of secondary fissures containing ladder veins of beresite (alplite) deposits in the Urals, *Izv. Akad. Nauk S.S.S.R.*, no. 5, pp. 57-66, 1949.

LOCON, H. PEUBE, Le quartz à Madagascar, *Bull. Géol. Madagascar*, v. 1, pp. 47-55, 1949.

LOOMIS, B. F., A pictorial history of the Lassen Volcano, Edwards Brothers, Ann Arbor, Michigan, 2nd ed., 109 pp., 1948.

NIKITIN, V. D., Fundamental characteristics of the ceramic pegmatites of Southern Karelia, *Zap. Vses. Min. Obsch.*, v. 78, pp. 207-226, 1949.

PARASCANDOLA, A., L'eruzione vesuviana del marzo 1944, *Soc. Real. Napoli*, v. 13 (4), pp. 285-304, 1945.

PAVLOV, N. V., and KARSKY, B. E., On myrmekites in some basic rocks, *Izv. Akad. Nauk S.S.S.R.*, no. 5, pp. 128-137, 1949.

PERRIN, R., and ROUBAULT, M., Applications d'études récentes sur les diffusions de faits géologiques, *Bull. Géol. Soc. France*, v. 19 (5), pp. 3-14, 1949.

PETERLONGO, JEAN, Les prismes de basalte, *Rev. Sci. Nat. d'Auvergne*, v. 14, pp. 127-134, 1948.

RADICE, MARIA MAGDALENA, Observaciones sobre La Llamada "Labradorita de Piriápolis," Notas 14, Museo de la Plata, *Geol.*, no. 52, 1949.

RICHTER, GERHARD, Geologische Gesetzmässigkeiten in der Metallführung des Kupferschiefers, *Archiv. Lagerst.*, Berlin, v. 73 (N.F.), 61 pp., 1941.

SCHERILLO, A., Le lave attuali del Vesuvio; Nov. 1941 and Feb. 1942, *Rend. Accad. Sci. Fis. and Mat.*, Soc. Real. Napoli, v. 13 (4), pp. 66-68, 1945.

SCHNEIDERHOHN, H., Schwespatgänge und pseudomorphe Quarzgänge in Westdeutschland, *Neues Jb. Min. Geol. Pal.*, pt. A, pp. 191-202, 1949.

SIMMONS, HAROLD, and BIDWELL, RICHARD MACPHERSON, Solubility measurements in the critical region, *Chem. Rev.*, v. 44, pp. 477-513, 1949.

STARRABBA, F. STELLA, Una problematica roccia siciliana, la "gulmarrite," *Not. Mineral. siciliana e calabrese*, no. 3, 27-39, 1949.

VUAGNAT, MARC, Variolites et splittes, Comparaison entre quelques pillows lavas britanniques et alpines, *Arch. Sci.*, Geneva, no. 2, pp. 223-236, 1949.

WELLS, A. K., Silica percentage as a factor in igneous rock classification, *Min. Mag.*, v. 27, pp. 688-692, 1949.

BIBLIOGRAPHY: TECTONOPHYSICS

ALAISTRUE, EDUARDO, and PRIETO, ILDEFONSO, Estratigrafía y tectónica de la Sierra de Esparteros, *Inst. Geol. Min. España*, no. 18, pp. 21-40, 1948.

ANDREATTA, C., La tettonica "a vortici" nei monti della Val di Sole, *Atti Accad. Naz. Lincei*, v. 5, pp. 60-67, 1948.

BARBOSA, OCTAVIO, Contribuição, a geologia do centro de Minas Gerais, *Miner. Metal.*, Brazil, v. 14, pp. 3-19, 1948.

BATY, V., Remarque sur le processus de subsidence, *Soc. Géol. Belg.*, v. 71, pp. 443-448, 1948.

- BENTZ, A. (Ed), *Erläuterungen zur geotektonischen Karte von Nordwestdeutschland, Reichsamt für Bodenforschung, Hannover-Celle*, 235 pp., 1949.
- BESAIRE, H., *Considérations sur le massif cristallin de Madagascar*, Bull. Géol. Madagascar, v. 1, pp. 9-11, 1949.
- BONTE, A., and RICOURE, J., La "Faille de Charlemont" et ses abords, Bull. Soc. Géol. France, v. 18 (5), pp. 629-644, 1948.
- BRIDGMAN, P. W., Effect of hydrostatic pressure on plasticity and strength, Research, v. 2, pp. 550-555, 1949.
- CASTANY, G., Phénomènes de subsidence plioquaternaire en Tunisie, Bull. Soc. Sci. Nat. Tun., v. 2, pp. 4-12, 1949.
- DANILOVICH, V. N., New data on the Angar Thrust, Izvest. Akad. Nauk.S.S.S.R., Ser. Geol., no. 4, pp. 69-77, 1949.
- EGELER, C. G., On metamorphic rocks from the island of Kabaena in the East Indian Archipelago, Kon. Neder. Akad. Wet., v. 52, pp. 551-562, 1949.
- EXNER, CHRISTOF, Tektonik, Feldspatausbildung und deren gegenseitige Beziehungen in den östlichen Hohen Tauern, Tsch. Min. Pet. Mitt., v. 1 (3), pp. 197-284, 1949.
- FAIRBAIRN, H. W., Structural petrology of deformed rocks Addison-Wesley Press, Cambridge, Mass., 2nd ed., 344 pp., 1949.
- FURRER, Max, Der subalpine Flysch nördlich der Schrattefluh (Entlebuch, Kt. Luzern), Ec. Géol. Helv., v. 42, pp. 11-154, 1949.
- FURRER, HEINRICH, Die geologie des Mont Bonvin nördlich Sierre, Wallis, Ec. Géol. Helv., v. 42, pp. 13-22, 1949.
- GANDOLFI, R., La faglia dello Staffora, Sue caratteristiche in rapporto al sistema di fratture nel Vogherse, Atti Acad. Naz. Lincei, v. 5, pp. 67-70, 1948.
- GERMAN SCIENCE, Mechanics of rigid and elastic bodies, Fiat Review, 1939-1946, Applied Mathematics, pt. II, 161 pp., 1948.
- GIGNOREX, M., La tectonique d'écoulement par gravité et la structure des Alpes, Bull. Soc. Géol. France, v. 18 (5), pp. 739-764, 1948.
- GREEN, HENRY, Industrial rheology and rheological sciences, John Wiley and Sons, 311 pp., 1949.
- GREENLY, EDWARD, The cleavages of Mon and Arvon, Proc. Liverpool Geol. Soc., v. 20, pp. 23-37, 1949.
- GROGAN, ROBERT, M., Present state of knowledge regarding the Pre-Cambrian Crystallines of Illinois, Trans. Ill. State Acad. Sci., v. 42, pp. 97-102, 1949.
- HASLER, P., Geologie und Petrographie der Sambuco-Massari-Gebirgsgruppe zwischen der oberen Valle Leventina und Valle Maggia im nördlichen Tessin, Schw. Min. Petr. Mitt., v. 29, pp. 50-155, 1949.
- HEYBROEK, P., and ZWART, H. J., The overthrusts between Teikersjón and Marsjón, Dalsland, Geol. Fören. Stockholm, v. 71, pp. 425-434, 1949.
- HIRTZ, P., L'anticlinal du Gros Foug au N de Serrières-en-Chatagne, Bull. Géol. Soc. France, v. 19 (5), pp. 161-166, 1949.
- ITEN, WERNER B., Zur Stratigraphie und Tektonik der Zone du Combin zwischen Mettelhorn und Turmtantal (Wallis), (V-XII), Ec. Geol. Helv., v. 41, no. 2, pp. 141-246, 1948.
- JARDETZKY, W., On the dynamics of the Earth's crust, Bull. Soc. Sci. Let. Poznań, Ser. B., v. 9, pp. 3-24, 1948.
- KEDEL, J., Estudios sobre estructuras hercínicas en la margen oeste de la cuenca frontón de la de Tonal, provincias de Mendoza y San Juan, Bol. Acad. Nac. Cién. Argentina, v. 38, pp. 253-346, 1949.
- KORDIUK, BOHDAN, Zur Entwicklung des subalpinen Molassetroges, Abh. Preuss. Geol. Landes., Berlin, v. 187, (N.F.), pp. 1-47, 1938.
- KUHLMAN, DORIS, and MASING, GEORG, Untersuchungen zur plastischen Deformation an Kupferdraht, Metallkunde, v. 39, pp. 361-375, 1948.
- KÜHN, OTHMAR, Zur Stratigraphie und Tektonik der Grossausschichten, Sitz. Östen. Akad., Wiss., Math.-natur. Kl., pt. I, v. 156, pp. 181-200, 1947.
- LAPADU-HARGUES, P., Contributions aux problèmes de l'apport dans le métamorphisme, Bull. Géol. Soc. France, v. 19 (5), pp. 89-110, 1949.
- LAUTEL, R., Note au sujet des roches des feuilles Ambatomanity et Andranomavokely et de leur position dans la classification des roches cristallines de Madagascar, Bull. Géol. Madagascar, v. 1, pp. 27-29, 1949.
- LESLIE, J. R., and CHESMAN, W. J., An ultrasonic method of studying deterioration and cracking in concrete structures, J. Amer. Conc. Inst., v. 21, pp. 17-36, 1949.
- LETOURNEUR, J., Sur la position tectonique d'un affleurement permien bordant le bassin houiller de Champagnac, Bull. Géol. Soc. France, v. 19 (5), pp. 175-180, 1949.
- MA, TING YING H., Diastrophic movements in Eastern Asia since the end of the Tertiary, Acta Geol. Taiwanica, v. 2, pp. 67-76, 1948.
- NEVSKII, V. A., Forms of folds on the southern slope of the Iahma range, Izvest. Akad. Nauk.S.S.S.R., Ser. Geol., no. 4, pp. 57-68, 1949.
- PALM, J. H., Stress-strain relations for uniform monotonic deformation under triaxial loading, Appl. Sci. Res., v. A-2, pp. 54-92, 1949.
- PERRONOD, A., Remarques tectoniques sur les environs de Morteau, Bull. Géol. Soc. France, v. 19 (5), pp. 85-88, 1949.
- PICARD, L., La structure de nord-ouest de l'Argentine avec quelques réflexions sur la structure des Andes, Bull. Soc. Géol. France, v. 18 (5), pp. 765-846, 1948.
- RIITTMANN, A., Le temperature nella crosta e l'orogenesi, Soc. Real. Napoli, v. 13 (4), pp. 250-261, 1945.

- ROQUES, M., Le Précambrien de l'Afrique Occidentale Française, Bull. Soc. Géol. France, v. 18 (5), pp. 589-628, 1948.
- SAVELEV, A. A., New data on the tectonics of the northern part of the Mangishlak Mountain system, Dokl. Akad. Nauk. S.S.S.R., v. 68, pp. 569-572, 1949.
- SODER, PIERRE ALBERT, Geologische Untersuchung der Schrattefluh und des südlich anschliessenden Teiles der Habkern-Mulde, Ec. Géol. Helv., v. 42, pp. 23-34, 1949.
- STILLE, HANS, Das Leitmotiv der Geotektonischen Erdentwicklung, Deut. Akad. Wiss. Berlin, no. 32, 27 pp., 1949.
- SUESCÚN, DARIO, and TABORA, BERNARDO, Analysis de las condiciones tectónicas en los túneles No. 1 y No. 2 del Ferrocarril Ibagué-Armenia-Frente de Ibagué, Dyna (Medellín, Colombia) no. 83, pp. 15-20, Nov. 1949.
- SVOBODA, JOSEF, and PRANTL, FERDINAND, The stratigraphy and tectonics of the early Paleozoic strata in the vicinity of Chýnčice (Central Bohemia), Sborník Stat. Geol. Ust. Rep. Českoslov., v. 15, pp. 1-40, 1948.
- TAUSON, L. V., On the energy of the lattice of silicates, Dokl. Akad. Nauk.S.S.S.R., v. 67, pp. 687-690, 1949.
- TRÜMPY, RUDOLF, Der Lias der Glarner Alpen, Denk. Schweiz. Natur. Gesell., Zürich, v. 79, no. 1, 192 pp., 1949.
- TURNER, J. S., The deeper structures of Central and Northern England, Proc. Yorkshire Geol. Soc., v. 27, pp. 280-297, 1949.
- WAARD, D. de, Tectonics of the Mt. Aigoual pluton in the southeastern Cevennes, France, Kon. Nederland. Akad. Wetensch. 52, pp. 389-402, and 539-550, 1949.
- WEYNSCHENK, ROBERT, Beiträge zur Geologie und Petrographie des Sonnewendgebirges (Tirol) besonders der Hornsteinbreccien, Schlern-Schriften (Univ. Innsbruck), no. 59, 66 pp., 1949.
- ZÖLLICH, MARTIN S., Zur Deckenfrage in Mittelharz, Abh. Preus. Geol. Landes, Berlin, v. 191 (N.F.), pp. 1-145, 1939.

NOTES AND PERSONALIA

NOTES

Corrigenda--The following correction is noted in the Transactions: Vol. 30, October 1949, in the paper by R. G. Folsom, p. 697, the figure title was inadvertently omitted and this should read, "Fig. 5--Damping disc system."

The following corrections are noted in the Transactions: Vol. 30, December 1949, in the paper by Ralph W. Powell, page 875, the last line of the abstract, following the comma, should read "for non-turbulent, turbulent, and ultra-rapid flow." On page 876, second line below Figure 1, change "before the 1946 paper" to "In the 1946 paper." On the same page in the second line below Figure 2, "ε" was omitted before the word "term." On page 877, second line above equation (7) "ε" should be replaced by "ε_k."

Meetings of the International Unions--The Ninth General Assembly of the International Union of Geodesy and Geophysics will be held in Brussels, Belgium, August 21 - September 1, 1951. For further information, see Special Announcements in this and subsequent issues of the Transactions.

The International Union of Crystallography will hold its Second International Congress in Stockholm, Sweden, June 27 - July 3, 1951. Further information may be secured from the General Secretary, R. C. Evans, Cavendish Laboratory, Cambridge, England. The Chairman of the U. S. National Committee is A. L. Patterson, Institute for Cancer Research, Corinthian Avenue and Poplar Street, Philadelphia 30, Pa.

The Seventeenth Congress of the International Geographical Union will be held in Washington, D. C., August 8 - 13, 1952. Further information can be secured through the General Secretary, George H. T. Kimble, Department of Geography, McGill University, Montreal 2, Que., Canada. The Chairman of the U. S. National Committee is Wallace W. Atwood, Jr., Research and Development Board, Department of National Defense, Washington 25, D. C.

Centenary of the Royal Meteorological Society--The Royal Meteorological Society will celebrate its Centenary in March and April 1950, including a four-day scientific program to be held at Oxford University, March 28 - 31. Members of AGU are invited to attend. Those who believe it will be possible for them to attend should get into touch with the office of AGU or write directly to the Secretary of the Centenary Committee, O. M. Ashford, 49 Cromwell Road, London, S.W. 7, England.

Bulletin 12b of the Association of Terrestrial Magnetism and Electricity, IUGG giving geomagnetic indices, K and C, for 1948 is now available for distribution. This was prepared by H. Herbert Howe and Evelyn K. Weismann with two appendices by Julius Bartels. Organizations and individuals interested in securing copies should write to the Secretary of the International Association, J. W. Joyce, 6641 32nd Street, N. W., Washington 15, D. C.

Proceedings of the First Meeting of The Mixed Commission on Ionosphere have been published by the International Council of Scientific Unions and are available for distribution in the United States by J. W. Joyce. The text, mostly in English but partly in French and German, includes ten papers and reports presented at the meeting.

Resumption of publication of Gerlands Beiträge zur Geophysik--Gerlands Beiträge zur Geophysik, publication of which was suspended in the 61st volume in 1944, is resuming publication with the second number of volume 61. Two volumes of four numbers each will be published each year, according to work received from Richard Bock, Director of The Geophysical Institute at Potsdam, Germany. This publication has taken over the activities of Beiträge zur angewandten Geophysik until separate publication can be resumed.

Cruises of research vessels--The research vessel Atlantis of Woods Hole Oceanographic Institution sailed from Woods Hole on January 5, 1950, on a four-months cruise in the North Atlantic.

The research vessel John Biscoe has sailed to the relief of the Stonington Island Antarctic Expedition of the Graham Land Survey.

The research vessel Albatross III of the United States Fish and Wildlife Service sailed from Woods Hole on January 4, 1950, on a two-months cruise investigating hydrographic and fishing conditions over the Continental Shelf between Long Island, New York, and Little River Inlet, North Carolina.

The U.S.S. Rehoboth and San Pablo returned to Philadelphia on December 15, 1949, from a two-month oceanographic survey cruise in the North Atlantic.

The Norwegian sealing vessel Norseal left Cape Town, South Africa for Queen Maude Land on December 28, 1949, carrying the Norwegian-Swedish-British Antarctic Expedition under John Glaver. The expedition is scheduled to spend two years studying geophysical conditions on the Antarctic Continent.

The royal research ship William Scoresby has been recommissioned and will sail early in 1950 for a survey of South African waters under Archibald McFie.

New serial publications in Japan--Volume 1, Number 1 of Geophysics, Fifth Series of Science Reports of Tohoku University, Sendai, Japan, dated February, 1949, has been received in the United States. Some items in this first issue appear in the bibliographic material of this number of the Transactions. The editors are Saemon Taro Nakamura, Yoshio Kato, and Gi-ichi Yamamoto.

Volume 1, Number 1 of the Journal of Geomagnetism and Geoelectricity, published in Kyoto in March, 1949, has also been received. This is the official publication of the Japanese Society of Terrestrial Magnetism and Electricity, and is currently published twice a year with the hope that it will become a quarterly publication. The Chairman of the Editorial Board is M. Hasegawa of Kyoto University. These items are also included in the bibliography of this issue of the Transactions.

Publication of The Geophysical Magazine has also been resumed. Volume 21, Number 1, May, 1949, has been received, and papers in this and earlier recent numbers are listed in this issue of the Transactions. This is a publication of the Central Meteorological Observatory in Tokyo.

Seminars of the Geophysical Research Directorate--Seminars of the Geophysical Research Directorate, Cambridge Field Station of the U. S. Air Forces are continuing at the Watertown, Massachusetts arsenal in a broad field of geophysical subjects bearing heavily on the atmosphere. At the time of going to press, no subjects later than February 10 are available. Interested persons should write to the Directorate for a calendar of the seminars.

Water conservation measures aid Louisville, Kentucky--Conservation measures adopted locally in Louisville, Kentucky, following the water shortage of 1943-1944 have been effective. Pumpage from the ground water has been reduced about one half, and artificial recharge has aided in reestablishing ground-water supplies over much of the area. Much of the water used for air conditioning is now being returned to ground-water storage. A report, prepared by M. I. Rorabaugh, District Engineer of the Ground-Water Branch, U. S. Geological Survey, is available in mimeographed form through the Survey office in Louisville.

Greek Hydrobiological Institute--A Greek Hydrobiological Institute was established in 1946 with Spyros Dantas as General Overseer. The Institute is charged with research in oceanography, biology, and limnology in the marine and fresh waters of Greece. An invitation is offered to American scientists to extend their research work into Greek waters, under which circumstances the Institute offers its collaboration and cooperation, both in laboratory and research-ship facilities.

Establishment of Philippine Geodetic and Geophysical Institute--The Government of the Philippines

has established a Philippine Geodetic and Geophysical Institute which is the adhering body to the International Union of Geodesy and Geophysics. Andres O. Hizon, Director of the Philippine Bureau of Coast and Geodetic Survey has been designated the first President of the Institute.

News Letter of the International Geographical Union--The International Geographical Union has begun the publication of a semi-annual news letter. The first number, dated January 1950, contains 24 pages of English text and 24 pages of French text. Copies may be secured through Secretary General George H. T. Krimble of the Department of Geography, McGill University, Montreal 2, Que., Canada.

Division of the Geophysical Institute in Trieste--The Geophysical Institute in Trieste has been divided into the Istituto Talassografico covering meteorology, oceanography, geochemistry, and closely related fields; and the Osservatorio Geofisico covering seismology, geodesy (including gravity), terrestrial magnetism, and closely related fields. Two new series of publications have been established.

New officers of the American Society of Limnology and Oceanography--The newly elected officers of the American Society of Limnology and Oceanography are: President, Arthur D. Hasler, Department of Zoology, University of Wisconsin, Madison, Wisconsin; Vice President, Edward S. Deevey, Osborn Zoological Laboratory, Yale University, New Haven, Connecticut; and Secretary-Treasurer, Thomas S. Austin, U. S. Navy Hydrographic Office, Washington 25, D. C.

PERSONALIA

Fred W. Blaisdell, Research Project Supervisor for the Soil Conservation Service at the St. Anthony Falls Hydraulic Laboratory, has been named the first recipient of the James W. Rickey Medal of the American Society of Civil Engineers for his paper, "Development and hydraulic design, St. Anthony Falls stilling basin."

Otto Burkard has been appointed Professor in charge of the Meteorological and Geophysical Institute of the University of Graz. The Institute now includes a seismological station and an ionospheric station, but seismological observations will not be resumed for some time because of alterations being made. The Institute is anxious to resume exchange arrangements with publications bearing on geophysics.

Arthur Casagrande, Professor of Soil Mechanics and Foundation Engineering at Harvard University, has been awarded the Arthur M. Wellington Prize of the American Society of Civil Engineers for his paper, "Classification and identification of soils."

William P. Creager, Consulting Engineer of Buffalo, New York, has been named an Honorary Member of the American Society of Civil Engineers.

George B. Cressey, Chairman of the Department of Geography at Syracuse University, was elected President of the International Geographical Union at the Sixteenth Congress of the Union in Lisbon in 1949, and is now on tour in Latin America in the interests of the International Geographical Union.

Serafin R. de Gula has returned to the Bureau of Coast and Geodetic Survey of the Philippines after a period of study and training with the U. S. Coast and Geodetic Survey.

V. G. Gabriel has been appointed Associate Professor of Geophysics at the Missouri School of Mines and Metallurgy.

George H. Hickox, Associate Director of the Engineering Experiment Station of the University of Tennessee, and Rex A. Elder, Director of the TVA Hydraulic Laboratory, are co-winners with Alvan J. Peterka of the James Laurie Prize of the American Society of Civil Engineers for their paper, "Friction coefficients in a large tunnel."

Irving Langmuir, 1932 Nobel Prize winner, has retired as Associate Director of the Research Laboratory from the General Electric Company. He will continue to be associated with the work as a consultant.

Gerard H. Matthes, Consulting Engineer, has been designated the recipient of the Norman Medal of the American Society of Civil Engineers for his outstanding paper, "Mississippi River cutoffs."

Harold M. Mooney has accepted a position as Assistant Professor of Geophysics at the University of Minnesota.

Ralph Parshall, retired irrigation engineer of the Department of Agriculture and Colorado A. and M. College, has been awarded the Gold Medal of the Colorado Engineering Council for his distinguished service to society and to the engineering profession.

Chas. S. Piggot, until recently Consultant of the Research and Development Board, has accepted a commission in the Foreign Service of the State Department and has been assigned as Scientific Attache to the American Embassy in London. He will also serve as Chief Science Officer and Chief of the American Science Mission, and in these capacities will also serve various government agencies and at the same time aid individual American scientists in the fulfillment of their missions. It is suggested that American scientists visiting Britain get into touch with Dr. Piggot.

Pierre St. Amand, until recently on the staff of the Geophysical Institute of the University of Alaska is now a graduate student at California Institute of Technology.

Stuart L. Seaton, Director of the Geophysical Institute, University of Alaska, has been elected a Fellow of the New York Academy of Sciences.

Fred W. Tresise has been appointed Associate Dean of the College of Engineering, Chicago Undergraduate Division of the University of Illinois.

Merle A. Tuve, Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, has been elected an Honorary Fellow of the Geophysical Institute of the University of Alaska.

C. F. Van Thullenar has returned from duty with the Military Government in Europe and is now Assistant Regional Director of the U. S. Weather Bureau in Kansas City, Missouri.

Vito A. Vannoni, Associate Director of the Hydrodynamics Laboratory and Assistant Professor of Hydraulics, California Institute of Technology, has been awarded the Karl Emil Hilgard Prize of the American Society of Civil Engineers for his paper, "Transportation of suspended sediment by water."

Theodore von Kármán, Director of the Guggenheim Aerodynamic Laboratory, California Institute of Technology, has been elected an Honorary Member of the American Society of Civil Engineers.

Isaiah Bowman, President Emeritus of Johns Hopkins University and world-renowned geographer, died suddenly January 6, 1950, at the age of 71. He was born at Waterloo, Ontario, Canada. He received his baccalaureate degree from Harvard University in 1905 and his doctorate from Yale University in 1909. He was the recipient of numerous honorary degrees and other awards. His outstanding promise as a geographer led to his appointment to an instructorship at Michigan State Normal College before he had received his degree, and in 1904, he received an Assistantship at Harvard University while still an undergraduate student.

His career took him to Yale University where he taught until 1915. For the next 20 years, he was the Director of the American Geographical Society, during which period he fulfilled many other important assignments, including acting as President Woodrow Wilson's Adviser during the Paris Peace Conference, and conducting expeditions to the Andes and the Rocky Mountains. In 1935, he became President of Johns Hopkins University, undertaking numerous other assignments during his incumbency and after his retirement in 1949. He considered his map of South America on the scale of 1:1,000,000 as his greatest contribution to the world's knowledge. He had been a member of AGU since 1944.

Charles James Clifford, Mathematician with the U. S. Coast and Geodetic Survey, died December 21, 1949, at the age of 55. He was born in Denver, Colorado, and secured his baccalaureate degree from the University of Colorado in 1924. Since 1925, he had served on the staff of the U. S. Coast and Geodetic Survey, where his chief work was in the field of vertical movements of the Earth's crust not associated with earthquakes. He had been a member of AGU since 1934.

Joseph Augustine Cushman, Geologist of the U. S. Geological Survey, and Director of the Cushman Laboratory for Foraminiferal Research in Sharon, Massachusetts, died April 16, 1949. He

was born at Bridgewater, Massachusetts, January 31, 1881. He received his baccalaureate degree from Harvard University in 1903, and his doctorate in 1909. In 1937, his Alma Mater awarded him the honorary degree of Doctor of Science. From 1913 to 1923, he was Director of the Museum of the Boston Society of Natural History, at the same time serving as Geologist with the U. S. Geological Survey. In 1923, he established his laboratory for research on foraminifera, continuing through most of the subsequent period on his work with the Geological Survey. He had been a member of AGU since 1945.

Robert E. Fellows, Geologist with the Alaskan Section of the U. S. Geological Survey, died suddenly at Windy, Alaska on September 19, 1949, at the age of 34. He was born at Schenectady, New York, and received both his baccalaureate and his master's degrees from the University of Rochester, the latter in 1941. He received the degree of Doctor of Philosophy from Johns Hopkins University in 1943 where he continued to do research work on quartzite fabrics. In 1943, he began service with the U. S. Geological Survey, doing extensive field work in Alaska, and serving as acting Chief of the Alaskan Section in the Washington office from October 1946 to October 1948, being relieved at his own request for further field work in Alaska. He had been a member of AGU since 1944.

Clarence Norman Fenner, Geologist and Mining Engineer died December 24, 1949, at the age of 79 in Clifton, New Jersey where he was born. He received the degree of Engineer of Mines from Columbia University in 1892, his masters degree in 1909, and his doctorate in 1910. His early career was devoted to mining geological work in various parts of North and South America. From 1910 to 1938 he engaged in petrological research with the Geophysical Laboratory of the Carnegie Institution of Washington, took part in a number of expeditions, and was author of numerous research papers. He had been a member of AGU since 1928.

Harry Durward Harradon, recently retired as Librarian and Translator for the Department of Terrestrial Magnetism, Carnegie Institution of Washington, died December 8, 1949. He was born in Auburn, Maine, September 22, 1883. He received his baccalaureate degree from Bates College in 1906, and attended American University in 1922-1923, and University of Paris in 1923-1924. He began his career as a teacher in 1906, teaching in various New England schools until 1912, when he began his services with the Carnegie Institution.

Many members will remember him as Secretary of the Section of Meteorology, in which office he served diligently and well from 1935 to 1947. At the time of his death, he was serving as Chairman of the AGU Committee on Statutes and By-Laws, which assignment he had filled for several years. He retired early in September, and was enjoying a vacation in Florida when he died. He had been a member of AGU since 1930.

Frank Baldwin Jewett of Short Hills, New Jersey died November 18, 1949, at the age of 70. He was born in Pasadena, California, and received his baccalaureate degree from Throop Polytechnic Institute (now California Institute of Technology) in 1898, and his doctorate from the University of Chicago in 1902. As a result of his outstanding work, he received honorary degrees from a number of universities, as well as other honors and awards.

After an early beginning in teaching at the University of Chicago and Massachusetts Institute of Technology, he entered the service of American Telephone and Telegraph Company, ultimately becoming Vice President in charge of Development and Research, and was President of the Bell Telephone Laboratory from 1925 to 1940. He retired as Vice President of the American Telephone and Telegraph in 1944, but had continued an active career as President of the National Academy of Sciences (1939-1947), and more recently as Chairman of the National Research Council's newly formed Building Research Advisory Board, and on other matters. He had just recently been awarded the Hoover Medal of the four Founder Engineering Societies. The medal was to have been presented at the January, 1950, meeting of the American Institute of Electrical Engineers. He had been a member of AGU since 1943.

William Frederick Prouty, Head of the Department of Geology and Geography, University of North Carolina, died June 27, 1949, at the age of 69. He was born at Putney, Vermont, received his baccalaureate degree at Syracuse in 1903, and his master's degree in 1904. He received his doctorate from Johns Hopkins in 1906. From 1906 to 1919, he was at the University of Alabama where he served as Professor of Geology and Chief Assistant State Geologist. He moved to the University of North Carolina in 1919 and became Head of the Department in 1932. During his career, he filled various important assignments as a consultant. He had been a member of AGU since 1935.

SPECIAL ANNOUNCEMENTS

Thirty-First Annual Meeting, Washington, D. C., May 1-3, 1950--With further regard to the Thirty-First Annual Meeting, the announcement of which appears on page 795 of the October, 1949 issue of the Transactions, the dates are May 1-3, 1950 (Monday to Wednesday). The meeting headquarters will be at the National Academy of Sciences - National Research Council Building at 2101 Constitution Ave. Arrangements are under way to provide sessions for all Sections, a general session, a symposium, and several joint sessions of two or more Sections. Place this on your agenda and make plans to come.

It is still not too late, in most instances, to place a paper on the program, but prompt action is essential. The closing date for titles with three copies of the abstract is March 10, 1950. Advise of the time required (most papers are allowed from ten to 20 minutes) and projection equipment needed. Send the information to the office of AGU at 1530 P Street, N. W., Washington 5, D. C., or the Secretary of the appropriate Section, listed in the October announcement cited.

Complete manuscripts should be forwarded in triplicate by April 10, 1950 in order that news releases may be prepared. If a paper has joint authorship, please indicate by whom it will be presented. Arrangements can be made for presentation of papers by authors who are unable to attend meetings. Advise whether the paper is being submitted for consideration for publication also, or only for presentation at the meeting. (Papers for publication only are also welcome for consideration for the Transactions. See pp. 159-160 of the February, 1949 issue of the Transactions for suggestions to authors.) In preparing papers for presentation, keep the style lucid to maintain the interest of the audience. Avoid complicated mathematical derivations, and as many back references as possible.

Make hotel or room reservations directly with the hotel of your choice well in advance of meeting dates. The Committee on Meetings has made block-bookings of rooms through the Washington Board of Trade indicated below, with the largest number at the Raleigh.

Raleigh Hotel, 12th St. and Pennsylvania Ave., N. W.; single \$4.50-\$7.00; double \$7.00-\$11.00.
Roger Smith Hotel, 18th St. and Pennsylvania Ave., N. W.; single \$4.00-\$6.00; double \$6.00-\$9.00.
Willard Hotel, 14th St. and Pennsylvania Ave., N. W.; single \$4.50-\$7.50; single without bath, \$3.50; double \$7.00-\$12.00; double without bath, \$5.00.

In writing for block-booked rooms, be sure and mention the AGU meeting. As single rooms are few, indicating willingness to share a room with another AGU member might be helpful in securing accommodations. Bear in mind that block-booked space not definitely reserved is no longer held two weeks before May 1, so place your reservation as soon as possible, and, at the latest, by April 15. Bear in mind that the space tentatively reserved at hotels is through their courtesy and if most of it is not taken up, they will hesitate to make reservations for us in subsequent years.

John Putnam Marble
Chairman, Committee on Meetings

Ninth General Assembly of the International Union of Geodesy and Geophysics to be held in Brussels, Belgium--The Ninth General Assembly of IUGG will be held in Brussels, Belgium, August 21 - September 1, 1951. A first call is being made for papers which will be handled by the several American Committees (the Sections) of the International Associations for coordination. Titles and abstracts of papers should be sent to the office of AGU as promptly as possible, and completed papers should be forwarded by autumn 1950. Various of the Associations are divided into Commissions or Sections on the specialties within the Association, and committees are being established for the handling of these papers. The Section of Hydrology has established Committees for Commissions on Surface Waters, Ground Waters, Snow and Glaciers, and the Committee on Land Erosion. The Association of Geodesy is divided into five Sections: Triangulation, Leveling, Astronomy, Gravity, and the Geoid. Papers for the program of this Association may be sent to AGU or direct to the Representative of the U. S. A. on the Association Council, Charles A. Whitten, U. S. Coast and Geodetic Survey, Washington, 25, D. C.

ADDITIONS TO THE MEMBERSHIP OF THE AMERICAN GEOPHYSICAL UNION,
JULY 11, 1949 TO JANUARY 10, 1950

- Abdullah, Dr. Abdul J., Room 24-512, Massachusetts Institute of Technology, Cambridge, Mass. (ce)
 Ackerman, Mr. Herman A., Socony Vacuum Oil Co., 26 Broadway, Room 720A, New York 4, N. Y. (ah)
 Albers, Mr. W. F., 614 Point St., Houma, La. (b)
 Alexander, Lt. William G., 1901 Washtenaw Ave., Ann Arbor, Mich. (c)
 Anderson, Mr. Daniel G., 207 Federal Bldg., Tacoma 2, Wash. (g)
 Andreasen, Mr. Gordon E., 5612 Hamilton Manor Dr., West Hyattsville, Md. (cg)
 Austin, Dr. J. M., Massachusetts Institute of Technology, Cambridge 39, Mass. (c)
 Baldwin, Mr. Sherd T., P. O. Box 912, Yuma, Ariz. (bce)
 Ballard, Prof. Stanley S., Dept. of Physics, Tufts College, Medford 55, Mass. (df)
 Bangs, Mr. Eugene F., 739 N. Knoxville St., Tulsa, Okla. (d)
 Barker, Mrs. Elsie M., 2320 Orchard Ave., Klamath Falls, Ore. (c)
 Baron, Mr. David, 2513 W. Fourth St., Los Angeles 4, Calif. (g)
 Bays, Dr. Carl A., P. O. Box 189, Urbana, Ill. (bg)
 Beagley, Mr. J. W., Geophysical Observatory, P. O. Box 374, Christchurch C. 1, New Zealand. (abcdeh)
 Berkenbosch, Mr. John C., 5756 Potomac St., St. Louis 9, Mo. (g)
 Beverage, Dr. Harold H., 66 Broad St., New York 4, N. Y. (d)
 Bissell, Dr. Harold J., Brigham Young University, Provo, Utah. (a)
 Bjorklund, Mr. Louis J., P. O. Box 282, Fort Morgan, Colo. (g)
 Blanchard, Mr. H. P., P. O. Box 533, Los Altos, Calif. (d)
 Boyer, Mr. Peter B., South Pacific Div., Corp. of Engr., Oakland Army Base, Oakland, Calif. (cg)
 Burrows, Dr. Chas. R., 116 Mitchell St., Ithaca, N. Y. (cd)
 Bush, Mr. Frederic A., Sinclair Oil Corp., 630 Fifth Ave., New York 20, N. Y. (abd)
 Callahan, Mr. Cornelius J., 4200 Wheeler Road, S. E., Washington, D. C. (c)
 Calvin, Capt. Charles B., P. O. Box 344, Randolph Field, Texas (ce)
 Cameron, Mr. W. M., Pacific Oceanographic Group, Pacific Biological Sta., Nanaimo, B. C., Canada. (ce)
 Campbell, Mr. Francis F., P. O. Box 2040, Tulsa 2, Okla. (bh)
 Carpenter, Mr. Archer B., U. S. Weather Bureau, Airport Sta., Salt Lake City 3, Utah. (c)
 Charney, Dr. Jule G., 7C Goodman Road, Princeton, N. J. (c)
 Chayes, Dr. Felix, Geophysical Laboratory, Carnegie Institute of Washington, Washington 8, D. C. (fh)
 Chow, Mr. Carl, c/o Mr. Lien-Yu Ho, 3823 Beecher St., N. W., Washington 7, D. C. (a)
 Clark, Dr. A. R., Dept. of Physics, University of British Columbia, Vancouver, B. C., Canada (abd)
 Coates, Prof. Donald R., 432 SW 16th St., Richmond, Ind. (fg)
 Cowen, Mr. Robert C., 331 Huntington Ave., Boston 15, Mass. (c)
 Cragwall, Mr. Joseph S., Jr., P. O. Box 1287, Baton Rouge, La. (g)
 Cramer, Dr. Harrison E., Round Hill, South Dartmouth, Mass. (c)
 Crum, Mr. Charles K., 1045 Lewellen St., Wichita 5, Kans. (c)
 Cunningham, Mr. William J., P. O. Box 1590, Tulsa, Okla. (b)
 Daines, Mr. Nolan H., P. O. Box 780, Grand Junction, Colo. (g)
 Dawson, Maj. William S., Hq. Airways and Air Communication Service, Washington 25, D. C. (cd)
 de Guia, Mr. Serafin R., Bureau of Coast and Geodetic Survey, Binondo, Manila, Philippines (d)
 Delgado, Mr. Ramon Antonio, Valverde (Mao), Dominican Republic, W. I. (g)
 Dempsey, Mr. William J., 613 Monroe St., N. E., Washington 17, D. C. (d)
 Dethier, Mr. Bernard E., Nazareth College, Nazareth, Mich. (de)
 Dickey, Mr. Woodrow W., 1918 Havana St., Aurora, Colo. (c)
 Dinegar, Mr. Robert H., 126 Davis Ave., White Plains, N. Y. (c)
 Dommes, Mr. Charles J., 12232 La Malda St., North Hollywood 1, Calif. (g)
 Duque, Maj. Elpidio, Research and Development Div., HNF Camp Murphy, Philippines (d)
 Duvall, Mr. Wilbur L., 5 Forestway Rd., Greenbelt, Md. (bh)
 Eady, Comdr. Jack A., P. O. Box 99, McLean, Va. (a)
 Fallon, Mr. Gerald J., 116 McIntyre Pl., Forest Home, Ithaca, N. Y. (aeg)
 Fan, Mr. Paul En Kun, 110 Wakewa Ave., South Bend, Ind. (g)
 Fehling, Mr. David M., 628 26th St., Santa Monica, Calif. (c)
 Ferguson, Mr. James L., 301 S. Lee St., Americus, Ga. (c)
 Finley, Mr. William L., 2725 Ashby Pl., Berkeley 5, Calif. (cg)
 Finton, Maj. James R., 304 No. Jackson St., Arlington, Va. (ce)

- Fletcher, Mr. Herbert C., 1425 Adelaide Dr., Tucson, Ariz. (fg)
 Fogel, Mr. Martin M., Dept. of Agricultural Engr., South Dakota State College, Brookings, S. Dak. (g)
 Gabriel, Dr. V. G., P. O. Box 213, Rolla, Mo. (abdefh)
 Garrett, Mr. Richard A., 931 Garfield Ave., Topeka, Kans. (acg)
 Gates, Mr. Howard P., U. S. Navy Electronics Lab., San Diego 52, Calif. (d)
 Girtan, Mr. Charles S., 1224 Elm Ave., Glendale 1, Calif. (c)
 Gleeson, Prof. Thomas A., Dept. of Meteorology, Florida State University, Tallahassee, Fla. (c)
 Godfrey, Mr. Richard G., 711 W. Harvard St., Champaign, Ill. (cg)
 Gosewisch, Mr. Guy N., 3309-A Terrace Dr., Washington 20, D. C. (c)
 Goshorn, Mr. John D., P. O. Box 383, Billings, Mont. (g)
 Hackett, Mr. O. Milton, P. O. Box 948, Riverton, Wyo. (efg)
 Hagan, Dr. Robert M., Div. of Irrigation, University of California, Davis, Calif. (g)
 Hales, Prof. J. Vern, 1202 Fourth Ave., Salt Lake City 3, Utah (cdeg)
 Hall, Mr. Robert B., U. S. Geological Survey, P. O. Box 360, Grand Junction, Colo. (ah)
 Hallborg, Mr. Henry E., 26 Macopin Ave., Upper Montclair, N. J. (d)
 Halsey, Prof. James Frederic, 121 Talbot Laboratory, University of Illinois, Urbana, Ill. (g)
 Hamilton, Mr. Harry L., Jr., Apt. 102, 2226 Washington Ave., Silver Spring, Md. (c)
 Hammons, Mr. Frans H., P. O. Box 757, Smithville, Texas (abcd)
 Harmen, Mr. Raymond A., Landing Aids Exp. Sta., Arcata, Calif. (cg)
 Hass, Mr. William A., U. S. Weather Bureau, Buffalo, N. Y. (c)
 Haupt, Mr. Harold F., Boise Research Center, P. O. Box 162, Idaho City, Idaho (cg)
 Helman, Maj. Carl H., Jr., 3401 Tech. Tng. Sqn., Keesler A. F. B., Miss. (c)
 Helmers, Mr. Austin E., Forest Experiment Station, Missoula, Mont. (cg)
 Hendricks, Capt. Clyde V., AF Cambridge Research Lab., 230 Albany St., Cambridge 39, Mass. (bcdeg)
 Henry, Dr. Laura M., Dept. of Zoology, Florida State University, Tallahassee, Fla. (c)
 Hess, Mr. John D., 4113 Park Pl., San Diego, Calif. (g)
 Heyndrickx, M. Gerard A. T., 52 rue de l'Ecole, Mont St. Amand, Ghent, Belgium (g)
 Hirashima, Mr. George T., 225 Federal Bldg., Honolulu 2, T. H. (cg)
 Hirst, Mrs. Delma E. (Webb), 1332 21st St., N. W., Washington 6, D. C. (a)
 Hoffman, Mr. John F., 753 Seneca Ave., Brooklyn 27, N. Y. (acg)
 Hubbard, Mr. James L., P. O. Box 216, DeLand, Ill. (c)
 Hubert, Mr. Lester F., 5719 64th Ave., East Riverdale, Md. (ceg)
 Hudson, Mr. Joseph L., 2222 N. Kensington St., Arlington, Va. (c)
 Huff, Mr. Floyd A., State Water Survey Div., Urbana, Ill. (c)
 Hughes, Prof. R. J., Jr., P. O. Box 115, State College, Miss. (abcdeh)
 Hutchinson, Mr. Dale H., 412 Durham St., Palo Alto, Calif. (c)
 Irish, Prof. Sumner B., 203 Engineering Bldg., Princeton, N. J. (a)
 Irmay, Mr. S., Hydraulic Laboratory, Hebrew Institute of Technology, Haifa, Israel (ceg)
 Jachowski, Mr. Robert A., 771 Elm St., Denver 7, Colo. (abefgh)
 Jackson, Mr. Herbert H., Mountain Experiment Sta., T. V. A., Waynesville, N. C. (cg)
 Jacoby, Mr. Paul F., 395 Meadowbrook Ave., S. E., Warren, Ohio (c)
 Jafferis, Mr. Ted C., P. O. Box 19, Randolph Field, Texas (c)
 Jansen, Mr. Robert B., 1510 18th St., Apt. 10, Sacramento, Calif. (bg)
 Jardetsky, Dr. Wlacheslaw, 209 W. 97th St., Apt. 7A, New York 25, N. Y. (h)
 Johnson, Mr. Loyal A., 3417 Portland Ave., Minneapolis, Minn. (g)
 Joos, Mr. Lothar A., U. S. Weather Bureau, Madison 6, Wisc. (c)
 Kassander, Mr. A. Richard, Jr., 2105 Friley Rd., Ames, Iowa (bg)
 Keech, Mr. Charles F., Route 5, Lincoln, Nebr. (g)
 Keenan, Mr. Curtis H., 134 N. Atherton St., State College, Pa. (bde)
 Keller, Mr. George V., Penn State Apt. 15, State College, Pa. (d)
 Ketchum, Dr. Bostwick H., Buzzards Bay Ave., Woods Hole, Mass. (e)
 Kindel, Mr. George J., 1444 Steele St., Denver 6, Colo. (c)
 King, Miss Elizabeth, 2337 Ashmead Pl., N. W., Washington 9, D. C. (bdh)
 Kinnison, Mr. Hallard B., 207 Federal Bldg., Tacoma, Wash. (g)
 Kirkpatrick, Mr. Mark H., 213 Washington St., Blacksburg, Va. (gh)
 Klein, Mr. Howard, Rm. 301, 515 E. Second St., Little Rock, Ark. (g)
 Klein, Mr. William H., 12 H Plateau Pl, Greenbelt, Md. (c)
 Koffman, Mr. Louis A., 110 W. Cameron Rd., Falls Church, Va. (g)
 Krans, Mr. Frederick H., 920-A 20th St., Santa Monica, Calif. (c)
 La Coste, Dr. Lucien J. B., 3810 Speedway, Austin, Texas (ab)
 Lacy, Mr. R. J., American Smelting and Refining Co., 600 Pacific Natl. Life Bldg., Salt Lake City, Utah (bd)
 Ladenheim, Mr. H. Charles, Lincoln Hall, Cornell University, Ithaca, N. Y. (abefgh)
 Lawrence, Mr. John W., 1210 S. Lincoln Ave., Urbana, Ill. (g)
 Leatham, Mr. Robert Paul, 4505 Yarrow St., Wheatridge, Colo. (ceg)

- Leopold, Mr. George S., 110-39 69th Rd., Forest Hills, N. Y. (cg)
 Lettau, Dr. Prof. Heinz H., 270 Linwood Ave., Newtonville 60, Mass. (cdeh)
 Lewald, Prof. Charles E., Dept. of Civil Engineering, Washington University, St. Louis 5, Mo. (g)
 Li, Mr. Kuo Jun, c/o Kenneth Diau, 412 Western Ave., Urbana, Ill. (g)
 Lin, Mr. Pin-Nam, Iowa Institute of Hydraulic Research, Iowa City, Iowa (g)
 Lindholm, Mr. Curt F., P. O. Box 251, Schuylkill Haven, Pa. (g)
 Littleton, Mr. Robert T., 2002 Capitol Ave., Cheyenne, Wyo. (bg)
 Liu, Mr. Hsi-Tien, c/o Mr. Lee Chang, 10 Tung-Kung Rd., Tientsin, China (g)
 Lowry, Miss Elizabeth Jean, 140 E. Union St., Wytheville, Va. (fh)
 Ludwick, Mr. John, Jr., 3672 Strand Way, Mission Beach, Calif. (eg)
 Lyons, Mr. Allan W., P. O. Box 88, Pasadena 16, Calif. (h)
 MacNeill, Mr. Neil M., 615 Custer St., Brush, Colo. (g)
 MacQuown, Dr. W. C., Jr., 914 Central Bldg., Wichita, Kans. (abd)
 Mahanta, Mr. Paban Chandra, Geophysics Dept., Imperial College, South Kensington, London, S. W. 7, England (abdh)
 Manning, Dr. Lawrence A., 649 Alvarado Row, Stanford, Calif. (cd)
 Marlave, Mr. Elmer C., 4466 N. Park Dr., Sacramento, Calif. (g)
 Marr, Dr. John W., Chief, Arctic Section, ADTIC Air University Libraries, Maxwell Air Force Base, Ala. (cg)
 Martin, Lt. Edgar H., 6640 S. Greenwood Ave., Chicago 37, Ill. (c)
 Martineau, Mr. Donald P., 32 Main St., Auburn, Mass. (ce)
 McKim, Dr. V. Calvon, Fresno State College, Fresno 4, Calif. (bc)
 Meuschke, Mr. Jack L., 2623 Southern Ave., S. E., Washington 20, D. C. (d)
 Mikels, Mr. Frederick C., U. S. Geological Survey, 445 N. Pennsylvania St., Indianapolis 4, Ind. (g)
 Miller, Mr. Mearle M., 207 Federal Bldg., Tacoma, Wash. (g)
 Monroe, Mr. Roy H., P. O. Box 668, Safford, Ariz. (g)
 Moore, Mr. Albert M., 3317 N. E. 30th Ave., Portland 12, Ore. (g)
 Morelli, Prof. Carlo, Istituto Talassografico, Trieste (abcdh)
 Morrow, Mr. G. R., 2620 S. Columbia Pl., Tulsa, Okla. (bc)
 Mott, Mr. W. D., Australasian Petroleum Co., Port Moresby, Papua (bdeh)
 Mulholland, Mr. George I., 5842 Darlington Rd., Pittsburgh 17, Pa. (c)
 Nace, Mr. Raymond L., 2002 N. 14th St., Boise, Idaho (gh)
 Nakaya, Dr. Ukichiro, 3-287 Harajuku, Tokyo, Japan (cg)
 Nelson, Mr. T. W., 3013 Bryn Mawr Dr., Dallas 5, Texas (abgdh)
 Newell, Dr. Homer E., Jr., 8 Melbourne Ave., Silver Spring, Md. (cd)
 Newton, Lt. Col. Carroll T., St. Anthony Falls Hydraulic Lab., Hennepin Island, Minneapolis, Minn. (g)
 Olmsted, Mr. Frederick L., Olmsted Brothers, Brookline 46, Mass. (g)
 Olsson, Mr. B. H., Dominion Physical Lab., Gravefield Rd., Lower Hutt, New Zealand (bdh)
 Oppenheim, Mr. Melvin, 87-22 Springfield Blvd., Bayside, Long Island, N. Y. (c)
 Osborne, Mr. M. F. M., 124 Mohican Dr., S. E., Washington 20, D. C. (g)
 Parke, Dr. Nathan G., III, Spencer Brook Rd., Concord, Mass. (d)
 Parks, Mr. Mercer H., Humble Bldg., Houston 1, Texas (bce)
 Parson, Prof. Ruben L., East Tennessee State College, Johnson City, Tenn. (aceg)
 Patterson, Dr. Charles M., Gulf Research and Development Co., P. O. Drawer 2038, Pittsburgh 30, Pa. (cf)
 Paul, Mr. Marvin S., 2260 Grand Ave., Long Beach 4, Calif. (c)
 Pellegrini, Maj. Joseph J., 1010 Fowler St., Falls Church, Va. (a)
 Perry, Mr. Wayne B., 2916 NW 43rd St., Oklahoma City, Okla. (abdh)
 Peters, Mr. Jack W., Magnolia Petroleum Co., P. O. Box 900, Dallas, Texas (abdh)
 Pfeil, Mr. John S., Jr., 26 Walnut Hill Rd., Newton Center 59, Mass. (c)
 Phair, Dr. George, Apt. 33, 2230 Savannah Terrace, S. E., Washington 20, D. C. (fh)
 Pocinki, Mr. Leon, 1155 Dean St., Brooklyn 16, N. Y. (ce)
 Pollard, Mr. Robert T., 414 Terminal Bldg., Oklahoma, City, Okla. (g)
 Pratt, Mr. Wallace E., P. O. Box 209, Carlsbad, N. Mex. (bcefg)
 Price, Mr. Edgar P., 4832 Que St., Sacramento 16, Calif. (cdg)
 Price, Sr. Llewellyn I., Divisao de Geologia e Mineralogia, Ave. Pasteur 404, Praia Vermelha, Rio de Janeiro, Brazil (e)
 Ragle, Prof. Richard C., College, Alaska (h)
 Ramberg, Dr. Hans, Dept. of Geology, University of Chicago, Chicago 37, Ill. (fh)
 Rather, Mr. R. L., Jr., Woods Hole Oceanographic Institute, Woods Hole, Mass. (bde)
 Reedy, Mr. William W., P. O. Box 2779, Juneau, Alaska (cg)
 Rivas, Prof. Luis Rene, Dept. of Zoology, University of Miami, Miami, Fla. (eg)
 Robbins, Prof. James M., 83 Maplewood Ave., Maplewood, N. J. (ag)
 Rodgers, Mr. Paul A., Dept. of Geophysics, Colorado School of Mines, Golden, Colo. (d)
 Romero, Adolfo C., Division de Geodesia, Cartografia Nacional, Caracas, Venezuela (ad)

- Roschke, Mr. Walter H., Jr., 3909 A. Fillmore St., St. Louis 16, Mo. (cg)
 Rosenfeld, Mr. John L., Hill Bldg., Eighth St., Rolla, Mo. (fh)
 Sanford, Mr. J. Homer, 500 Fifth Ave., New York 18, N. Y. (g)
 Savage, Miss E. Lynn, 1535 W. Eighth St., Brooklyn 4, N. Y. (abfgh)
 Saville, Mr. Thorndike, Jr., 1015 Colusa Ave., Berkeley 7, Calif. (e)
 Schedler, Mr. George D., P. O. Box 1590, Tulsa, Okla. (bh)
 Schwartz, Mr. Henry W., 320 W. Pells St., Paxton, Ill. (c)
 Sekera, Dr. Zdenek, Dept. of Meteorology, University of California, Los Angeles 24, Calif. (ce)
 Sexton, Mr. Harold W., Route 3, Box 68, Bend, Ore. (fg)
 Sherman, Mr. Irving, Apt. 5, 5977 Franklin Ave., Hollywood 28, Calif. (ag)
 Sherman, Mr. Leon, 2634 N. Beachwood Dr., Los Angeles 28, Calif. (c)
 Sturna, Mr. Tomas, 284 Elm St., Gatineau (Mills), Que., Canada (a)
 Slosson, Mr. James E., 14730 Burbank Blvd., Van Nuys, Calif. (eg)
 Smith, Mr. Kenneth G., 600 W. 146th St., New York 31, N. Y. (bdg)
 Spitzer, Prof. Lyman, Jr., 16 Prospect Ave., Princeton, N. J. (cde)
 Stephenson, Mr. George K., 4701 DeMontluzin St., New Orleans, La. (g)
 Stewart, Mr. T. E., 3139 S. Stafford St., Arlington, Va. (d)
 Strub, Mr. Joseph H., Jr., 2715 Benton Blvd., Kansas City 3, Mo. (cg)
 Summersett, Mr. John, Jr., Star Rt. 2, Foster, Ore. (g)
 Swan, Dr. Emery F., Oceanographic Laboratories, Friday Harbor, Wash. (ceg)
 Thalmann, Dr. Hans E., Oil Properties Consultants, Inc., 709-711 S. Fair Oaks Ave., Pasadena 2, Calif. (e)
 Thomas, Capt. Charles W., 224 Old Customhouse, St. Louis 1, Mo. (e)
 Thompson, Mr. Andrew A., Friendship Hill, New Geneva, Pa. (bc)
 Thompson, Mr. Melvin L., P. O. Box 948, Riverton, Wyo. (cg)
 Tierney, Mr. J. Q., 5921 SW 59th St., Miami, Fla. (e)
 Toth, Mr. Albert S., 639 W. 207th St., New York 34, N. Y. (g)
 Tsuboi, Dr. Chuji, Geophysical Institute, Faculty of Science, Tokyo University, Tokyo, Japan (abdh)
 van Veen, Dr. Johan, Stalpertstraat 35, The Hague, The Netherlands (eg)
 van Wijk, Mr. A. M., Director, Hermanus Magnetic Observatory, Hermanus, South Africa (abcd)
 Venkateswarlu, Dr. K., Dept. of Geophysics, California Institute of Technology, Pasadena, Calif. (abcde fgh)
 Vernon, Mr. Edward M., Airport Sta., U. S. Weather Bureau, San Bruno, Calif. (c)
 Volk, Prof. Joseph A., 7135 Winchester Dr., Normandy, Mo. (bd)
 Weaver, Prof. John C., Dept. of Geography, University of Minnesota, Minneapolis 14, Minn. (ce)
 Webber, Prof. John P., COCTA, Ed. Nova Estacao de Passag., Aeroporto Santos Dumont 3 andar, Rio de Janeiro, Brasil (c)
 Webster, Mr. William M., 2607 East 2980 South, Salt Lake City, Utah (g)
 Wells, Mr. Joseph V. B., 801 E. Hillwood Ave., Falls Church, Va. (g)
 Werth, Mr. Glenn C., 560 S. Barrington Ave., Los Angeles 24, Calif. (bde)
 Whitaker, Mr. George L., P. O. Box 486, Cambridge, Nebr. (g)
 White, Mr. Gale, 6000 Lemmon Ave., Dallas 9, Texas (e)
 White, Mr. Walter S., 1033 Mine St., Calumet, Mich. (h)
 Witala, Mr. Sulo W., P. O. Box 407, Houghton, Mich. (g)
 Williams, Mr. Adrian H., 3621 28th St., N. W., Washington, 18, D. C. (g)
 Williams, Mr. Melvin R., P. O. Box 56, Montgomery 1, Ala. (g)
 Williams, Mr. Norman F., 2505 Montevallo Rd., Birmingham 9, Ala. (g)
 Wilson, Miss Ethel M., 9 K Parkway Rd., Greenbelt, Md. (g)
 Wootton, Dr. Donald M., Santa Barbara College, University of California, Santa Barbara, Calif. (eg)
 Wright, Mr. John E., 361 Vassar Ave., Berkeley 8, Calif. (bcg)
 Yates, Mr. Joseph C., P. O. Box 810, Roswell, N. Mex. (g)
 Zimmerman, Lt. Col. C. J., 312 Thayer St., Little Rock, Ark. (bg)

**FRIEZ INSTRUMENT DIVISION
BENDIX AVIATION CORPORATION**

Manufacturer of Meteorological Instruments

Taylor Avenue near Loch Raven Boulevard
Baltimore 4, Maryland

GEOPHYSICAL RESEARCH CORPORATION

Geophysical Prospecting
Application of Geophysical Methods in the Petroleum Industry

2607 North Boston Place
Tulsa 6, Oklahoma

KEUFFEL AND ESSER COMPANY

Drafting, Reproduction, and Surveying Equipment and Materials
Slide Rules Measuring Tapes

300 Adams Street
Hoboken, New Jersey

RANNEY METHOD WATER SUPPLIES, INC.

Ground Water Exploration and Development

841 Alton Avenue
Columbus 3, Ohio

RUSKA INSTRUMENT CORPORATION

Developers, Designers, and Manufacturers of Instruments for Field and Observatory Use
Magnetic, Geodetic, Seismic, and Meteorological Work

4607 Montrose, Boulevard
Houston 6, Texas

SEISMOGRAPH SERVICE CORPORATION

Seismic Exploration Service for
Oil and Gas Structures throughout the World

P. O. Box 1590
Kennedy Building
Tulsa 1, Oklahoma

SPRENGNETHER INSTRUMENT COMPANY

Manufacturer of Seismological and Geophysical Instruments
Instrumental Development and Research

4567 Swan Avenue
St. Louis 10, Missouri